Identification and synthesis of agrometeorological extreme weather indicators for the temperate-boreal zone

Louise Malmquist
louise.malmquist@slu.se

Swedish University of Agricultural Sciences, SLU

Department of Soil and Environment

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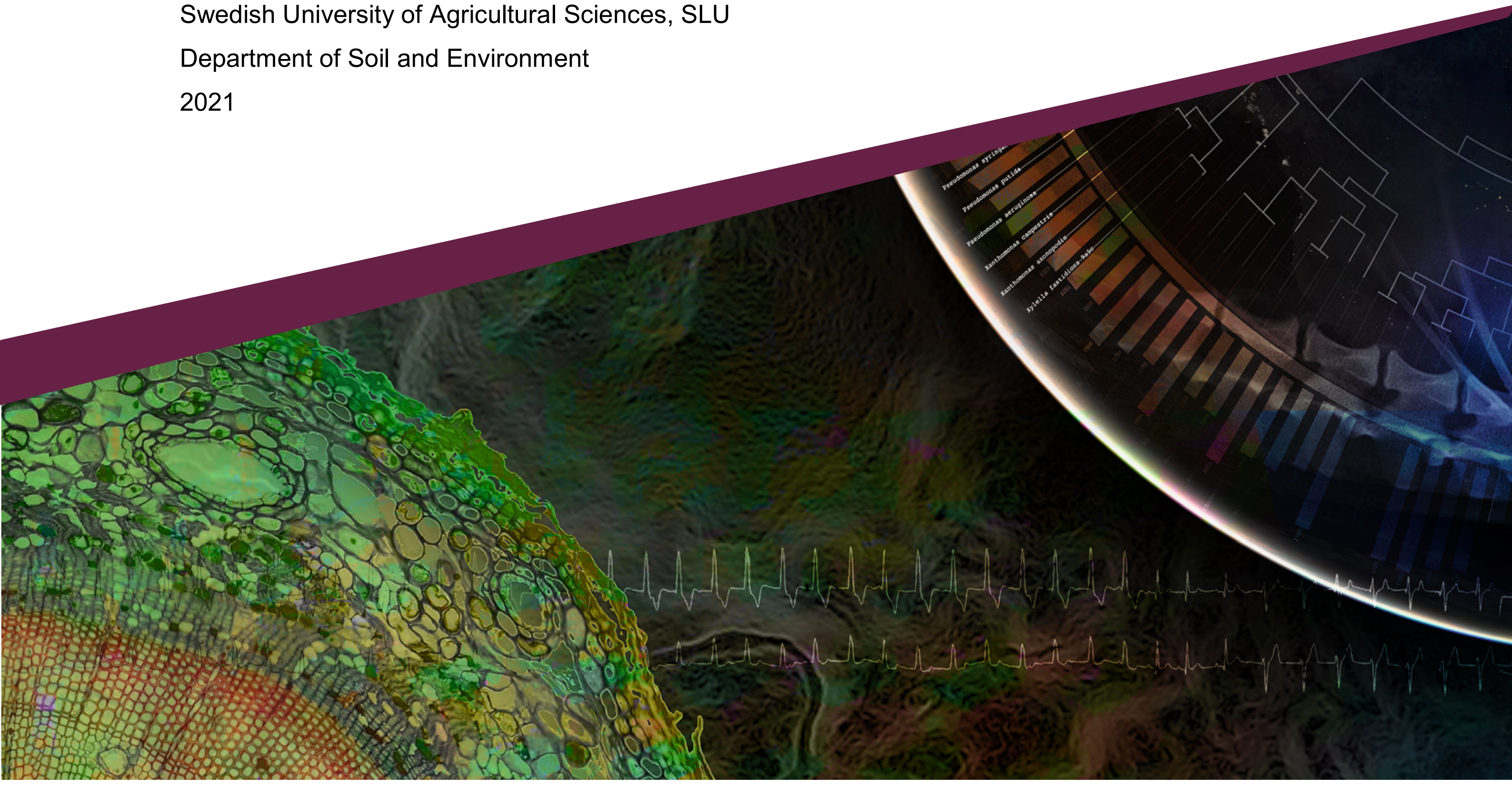

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Louise Malmquist

Swedish University of Agricultural Sciences,
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Abstract

Crop production is dependent on timeliness and circularity of weather parameters e.g. defined temperature thresholds and timeliness and volume of water supply. Yet due to erratic nature of weather patterns, cropping systems require good buffering capacity to various weather conditions. Due to climate change, there has been a shift in climate zones and thus conditions for crop production.

Climate projections indicate that the Nordic countries might experience elevated regional temperatures, which will partially be beneficial for e.g. elongated cropping season. However, synergetic effects from e.g. changed precipitation patterns might inhibit effects that otherwise would be beneficial. Additionally, projections suggest that also Nordic countries are vulnerable and subjected to experience shifts in weather patterns – enquiring mitigation and adaptation measures to sustain crop production.

Extreme weather are per definition rare. These events are classified differently depending on sector and system of interest. Agrometeorological extremes consider the relation of weather impact (direct- and indirect) on crop yield and related requirements on cropping conditions. Building resilience in agriculture towards weather related events enquire a defined extreme to explore required expectations of interventions.

This document is a review of quantitative extreme weather definitions linked to agricultural production in the Nordic countries. The objective is to answer how extreme weather is related to precipitation and temperature variations defined and quantified for impacts on crop production in the temperate-boreal zone. The emphasis have been on definitions of extreme temperature and precipitation.

The synthesis indicate that there is no unified definition of agrometeorological extreme event used in academics and that there is a substantial number of studies using meteorological definitions especially linked to extreme precipitation and drought events. (n =19 of 22 and n = 9 of 13 individual definitions respectively)

Contents

Background

Plant growth and development is dependent on climatic conditions and synergetic effects of weather parameters on daily basis as well as synergetic effects of consecutive weather events. Weather parameters are ever fluctuating, and open farming systems require good buffer capacity in the management to account for several different weather events impacting crops both directly- and indirectly - by effects on plant-soil-microbe interactions (e.g. Jia et al. 2019). If changes and specified weather events should be classified extreme however, depends on the system, impact variables that are in focus, as well as synergetic effects and feedback loops between related climate variables (WMO 2010; Seneviratne et al. 2012; TT-DEWCE WMO 2016; Zscheischler et al. 2020).

Since 1850, the three passed decades have been consecutive warmer (IPCC 2014). The previous last six-year period (2015-2020) have been the warmest since the mid-19th century (World Meteorological Organization 2021b), and new projections suggests that there is a 40% change of global average temperatures rises above 1.5 °C during the period 2021-2025 (World Meteorological Organization 2021a), which is the aimed limit (well below 2°C since prehistoric times) set by the Paris Agreement (United Nations Framework Convention on Climate Change 2016). Global warming additionally have potential to affect other large scale circulating systems (e.g. Lenton et al. 2019). However, these global average changes does not imply variation in regional climate change. Nor do they explicitly indicate inter- and intra-annual weather variations and shifts of their occurrence (Seneviratne et al. 2012).

Shifts in mean, variance and distribution of regional weather events (Seneviratne et al. 2012) are of large importance for crop production systems. Clustered projections (IPPC SR5) of crop yield from various locations globally under influence of climate change (mainly considering global average temperature increase up to 4°C); indicate both positive and negative yield changes. Yet with dominant yield decreases which increase in dominance to later part of 21st century (IPCC 2015). Projected effects of climate change on crop production indicate that Nordic countries will experience less temperature increase and precipitation decrease, compared to central and southern Europe (Trnka et al. 2011). Elevated temperatures and thus longer theoretical growth period has been brought up as a partly positive aspect in the Nordic countries (Olesen et al. 2012; Peltonen-Sainio & Jauhiainen 2014; Juhola et al. 2017). However interactions between parameters as dry periods and elevated temperatures might inhibit each other, limiting the actual potential of longer growth period (Trnka et al. 2011; King et al. 2018). Yield reducing effects and synergetic effects of weather events might be possible to reduce by considering maturing of crop species and variety. Yet there are multiple events to consider when adapting cropping systems to extreme weather impacts (Trnka et al. 2014). Thus, to plan actions of mitigation and adaption for crop production systems accordingly towards weather related disturbances, the extreme impact on the system must initially be defined.

The term *extreme* can be related to either the event itself, the potential hazard or the final impact caused by an individual, temporal and/or spatially combined event(s) (Zscheischler et al. 2020). *Agro-meteorological extremes* (mainly linked to drought) consider the relation of weather impact (direct- and indirect) on crop yield and related requirements on cropping conditions (Wilhite & Glantz 1985; Van Loon et al. 2016). Additionally, extreme events can be determined by various methods (e.g. Bärring et al. 2006; Fleig et al. 2011; Seneviratne et al. 2012; TT-DEWCE WMO 2016)). Quantitatively, extreme weather is defined by thresholds based on observed distributions of weather events, its impact on important sectors or parameters or various indices (Seneviratne et al. 2012; TT-DEWCE WMO 2016). Thresholds are based on historical data, including statistically rare values or events where one or more sectors experience negative impact (TT-DEWCE WMO 2016). Furthermore can extreme events be defined by statistical frequencies (often < 10th and > 90th percentiles of a dataset or defined return periods are been used, as well as even lower limits (> 70th percentile) (Bärring et al. 2006; Fleig et al. 2011). Definitions varies in relevance depending on field and purpose

(McPhillips et al. 2018) and some definitions might be problematic with a transition of distributions in weather patterns (Harrington & Otto 2018)

This document is a pilot study to explore quantitative definitions of extreme weather linked to agricultural production in the Nordic countries. The objective is to answer how extreme weather is related to precipitation and temperature variations defined and quantified for impacts on crop production in the temperate-boreal zone. The synthesis is supposed to assist further research projects linked to agriculture under in choosing a suitable definition of extreme events relevant for their research questions and studied agricultural system.

In this review, extreme events of temperature and precipitation is in focus as these have short and long-term implications for agricultural production. Other extreme events exists, e.g. heavy winds or hailstorms, which also have impact on agricultural production by possible mechanical damages. However, these events do not have as long-term impact on the overall crop production as temperature and precipitation, which are fundamental parameters for crop growth and -development as long as they are kept within tolerable levels.

Method

This review focuses within the zones of temperate- and sub-arctic climate where climatic conditions corresponds to Swedish agro-climatic zones (Beck et al. 2018; King et al. 2018; Ceglar et al. 2019) as where effects of different extreme weather events might have similar impact on cropping systems.

Literature for the two themes where mainly achieved through a partial systematic approach in the search engine Web of Knowledge[1] during the period January 2020 to November 2020. Terms used in search queries and per focus area are shown in Table 1. The terms where combined using the links "AND", "OR" and the bulleted sections in Table 1 were separated by parentheses. The search was complemented with secondary achieved references from reviewed publications from the initial search. Additional grey literature was obtained from webpages belonging to Swedish authorities by using the same terms as used in the initial search queries for Web of Knowledge.

References were initially included based on their title. If they had an initiation of including information on climate and extreme weather and agriculture. The references were secondly selected based on information in abstracts, if they mentioned quantitative analysis of extreme weather and impact on agriculture – focus on crop production.

From the fully read and included references, following information was collected. Note that not all information was available for all reviewed studies:

> Type of meteorological definition; country, duration of definition for extreme event; event magnitude (minimum and maximum values if a range); area specification for the event if relevant; percentiles for when the event is considered extreme related to a reference period; Threshold related to actual evapotranspiration and potential evapotranspiration; the author's own descriptive definition.

Table 1. Search queries for Extreme weather definitions. The queries where used in different combinations for the three categories with separation of "AND" or "OR" and parentheses separating the terms in the different paragraphs in the table

Terms in search queries
• Agrometeorology ; "extreme weather"; extreme weather; Extreme weather; extreme*; climate change
• Growing season;
• Temperature; winter; cold; hibernation; rest; sleep; dormancy; frost; freezing; hardiness; LT50
• downpour; downfall; cloudburst; "heavy rainfall"; flood*; precipitation; extreme precipitation; high precipitation; flooding; rainfall; storm
• drought; dryspell OR dry-spell; "dry spell"; "extreme precipitation"; heat wave; heatwave; heat-wave;
• agriculture; agricult*; farm*; crop*; crop; cultiv*; arable*; crop prod*
• Swed* OR Norw*; Finnish; Finl*; Finland; Finnish *; Denm*; Denmark; Danish*; Danish; Icel*
• soil saturation
• crop growth; crop development; aeration; * soil management*; water management
• water supply; water use; water requirement; crop water; drainage; water need*; transpiration; evapotranspiration; agrometeorolog*; hydrogeolog* OR hydrolog*;

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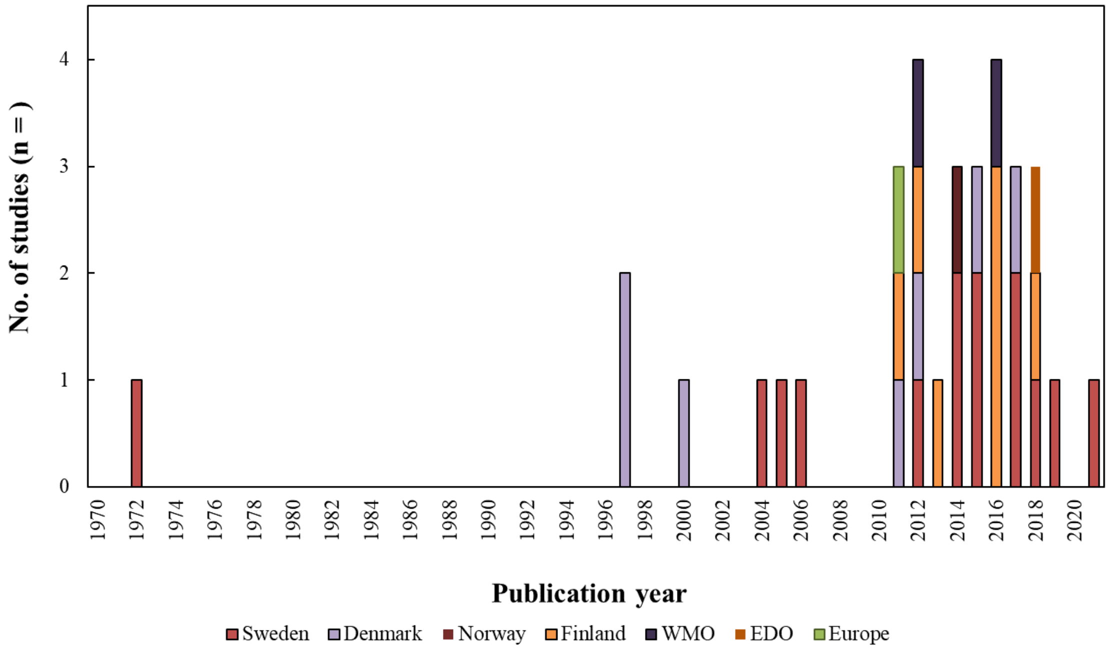
[1] *www.webofknowledge.com*

Indices and definitions for rainfall and temperature from an agro-meteorological lens

From a crop production perspective, impact of extreme weather events is especially vulnerable to rainfed cropping systems due to the dependence on a natural continuous water cycle and temperature conditions. This section presents definitions of extreme weather from studies focusing on agriculture and parameters that affect the definition of extreme weather from an agrometeorological perspective. Quantified thresholds Figure 4, Figure 5, Figure 6, Figure 7 and Figure 8 are based on n =33 references. A complete reference list is included in Appendix, Table 3. The reviewed studies are from Sweden (n = 14), Norway (n = 1), Denmark (n = 7) and Finland (n = 7). Additional four (n =4) references are from a European study regarding the continent's different agro-ecological zones, WMO and The European Drought Observatory. The literature is published after year 2000 except from two (n = 2) studies that are published 1972 and 1997 respectively (Figure 1)



From the 33 references, 88 individual quantitative definitions of extreme precipitation (n = 22), drought (n = 13), heat (n = 14), cold (n = 25) and aridity index (n = 14) where identified (Table 2). These numbers show an overall weight towards meteorological definitions related to precipitation, while temperature related definitions are more directly linked to impact on crops.

Table 2. Classification of reviewed extreme event indices/definitions as either meteorological or agrometeorological after definitions by Wilhite & Glantz (1985); Das et al. (2003); TT-DEWCE WMO (2016) and Van Loon et al. (2016)z

	Meteorological definition	Agrometeorological definition
High precipitation	19	3
Drought	9	4
Heat	3	11
Cold	10	15
ET_a/ET_p	-	14

Start- end and duration of cropping season and sowing conditions

Extreme weather from a crop production perspective should reflect impacts on growth, development and survival of crops (Barlow et al. 2015), as well as conditions for crop management. Important weather impacts occur both during the growth period as well as during winter dormancy of autumn sown crops. The growing season can be classified as the period when temperature and soil moisture sustain crop growth (Carter 1998). with sowing in Sweden occurring as soon as the soil is thawed and dried (Håkansson et al. 2002). The start of growth season is defined uniformly from various references. ETCCDI classifies the start as daily average temperature ≥ 5°C for six continuous days (Zwiers & Zhang 2009). Which is similar to the Swedish definitions e.g. a 24-hour average temperature > 5°C (Enghang et al. 2016) for at least 4-5 continuous days during spring (e.g. Carter, 1998; Johansson, 1973; Johnsson, 1972). Historically this period has not been set earlier than 15 days after a cold-period or if a significant snow cover occurs (Johansson 1973). An elaborative definition for spring related to Swedish agricultural conditions is "*...starts the first day of a seven day period with the daily average temperature above 3°C, yet earliest when the length of day is 9 hours and above. Spring lasts at least 2 weeks" p. 21* (Mattson et al. 2018). Day length > 9 hours take place approximately from 2nd to last week of February (SMHI 2020c). Average temperatures > 3 °C in Sweden has after the previous climatological reference period (1961-1990) started in March in southern Sweden, to May in the most Northern parts (SMHI n.d.). However, the new reference period set to 1991-2020, by the Swedish meteorological Institute for referring to deviations in weather occurrences (SMHI 2020e) (Figure 2). Thus, the criteria on day length might lose its relevance under climate change impact.

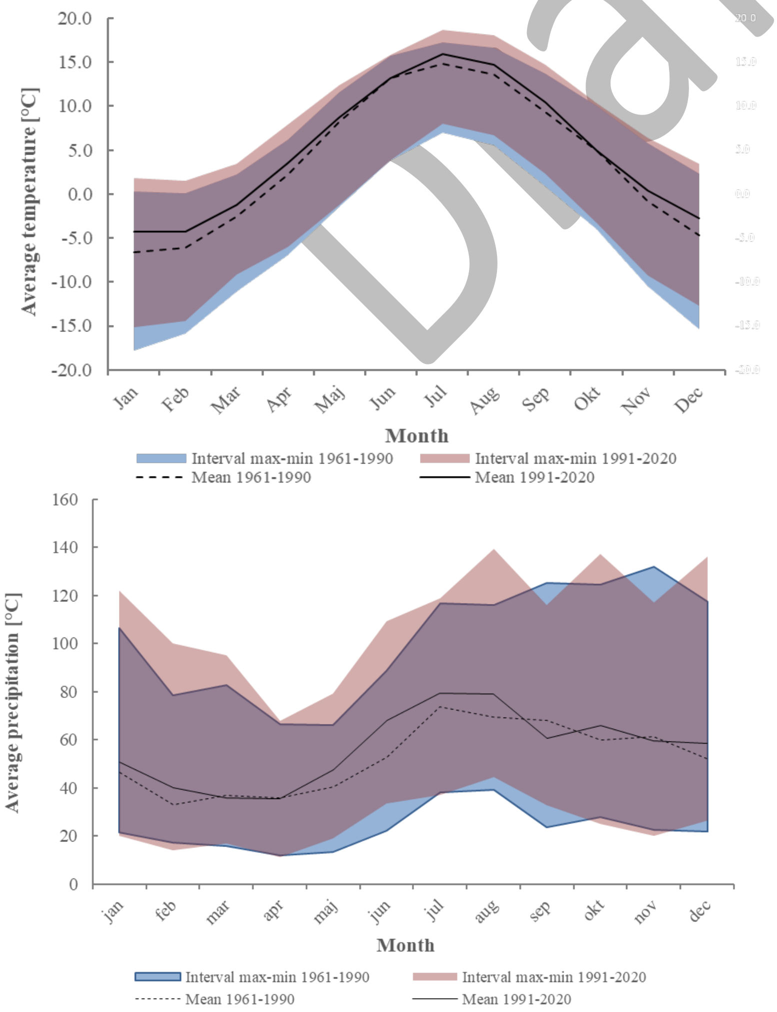
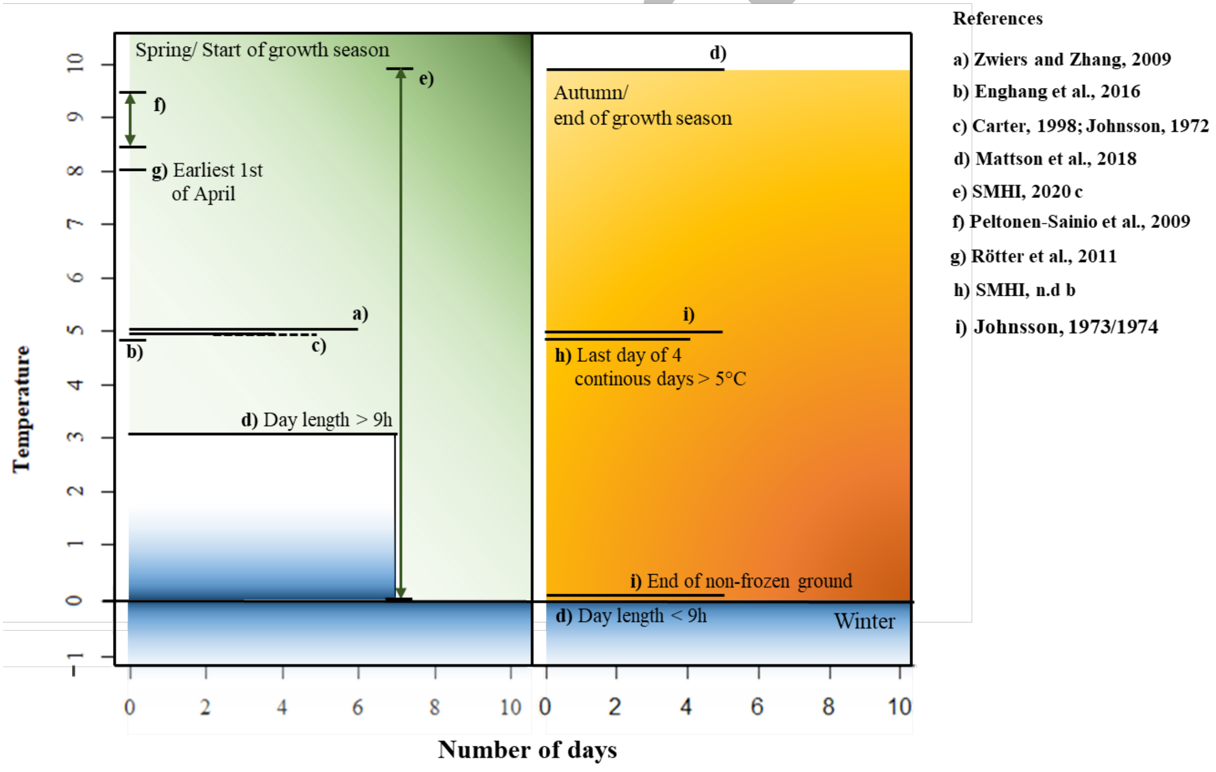


Figure 2. Shift in monthly average temperature and monthly precipitation between the previous (1961-1990) and the new (1991-2020) reference periods for statistical weather parameters. The Graphs are based on calculated from station data and represent Tmin, Tmax and Taverage of normalized observation values from nation-wide weather stations for the two parameters. Data series of normal temperatures and normal precipitation are provided by SMHI. Datasources: SMHI (2021) Normalvärden för temperatur. Available: https://www.smhi.se/data/ [2021-03-15] and] SMHI(2021) Normalvärden för nederbörd. Available: https://www.smhi.se/data/ [2021-03-15]

In comparison to above criteria, meteorological spring is classified as increasing daily average temperature > 0°C and < 10 °C over a period of seven continuous days (SMHI, 2020 c). Another example from a Finnish study classified the physiologically effective growing season by historical average sowing dates of spring cereals (reference year 1971-2000) and the temperature during sowing were 8.5-9.5 °C (Peltonen-Sainio et al. 2009). Additionally physiologically effective growing season from base temperatures of 0 °C or +5 °C for temperate crops (Peltonen-Sainio et al. 2009; Eckersten & Kornher 2012) and +6°C (Eckersten et al. 2012; Eckersten & Kornher 2012; Nkurunziza et al. 2014) or +10°C for maize (Peltonen-Sainio et al. 2009). Similarly, a threshold of 8 °C based on moving average temperature and earliest 1st of April was used by Rötter et al., (2011) while . Five degrees (+5 °C) is overall a threshold temperature for crop growth for several crop species as well as for ground frost to disappear (Carter 1998) see e.g. (Geisler 1983; Gunnarson 2012; Johnsson 2016). Furthermore, +5 °C is generally used as the base temperature when determining temperature sum during the cropping season. Additionally, Trnka et al. (2011) included criteria on minimum temperatures > 0 °C, no snow cover and evapotranspiration ratio $Et_a/ET_r > 0.4$ (see additional information in section *Drought and dryspells*). Yet, literature values of minimum germination



Start of growth season	Daily $T_{average} \geq 5$°C for 6 continuous days **OR** $T_{average} > 5$ °C for 4-5 continuous days during spring
Physiological effective growth season	$T_{average}$ during sowing 8.5-9.5 °C (based on historical average sowing dates 1971-2000) **OR** $T_{average} \geq 5$ °C (temperate crops) and ≥10°C (maize) **OR** $T_{average} \geq 8$ °C and earliest 1st of April
Spring	$T_{average} > 3$ °C and day length ≥ 9 h, lasting ≥ 2 weeks **OR** Increasing $T_{average} > 0$°C and < 10 °C for 7 continuous days (meteorological spring).
Autumn	$T_{average} \leq 10$ °C over 5 continuous days after 1st of August
End of growth season	Last day of 4 consecutive days with $T_{average} > 5$ °C **OR** $T_{average} < 5$ °C for five continuous days
End of non-frozen ground	$T_{average} < 0$ °C for 5 consecutive days or when snow cover develops
Winter	$T_{average} < 0$ °C **AND** day length < 9 h **AND** starts earliest 2 weeks after start of autumn.

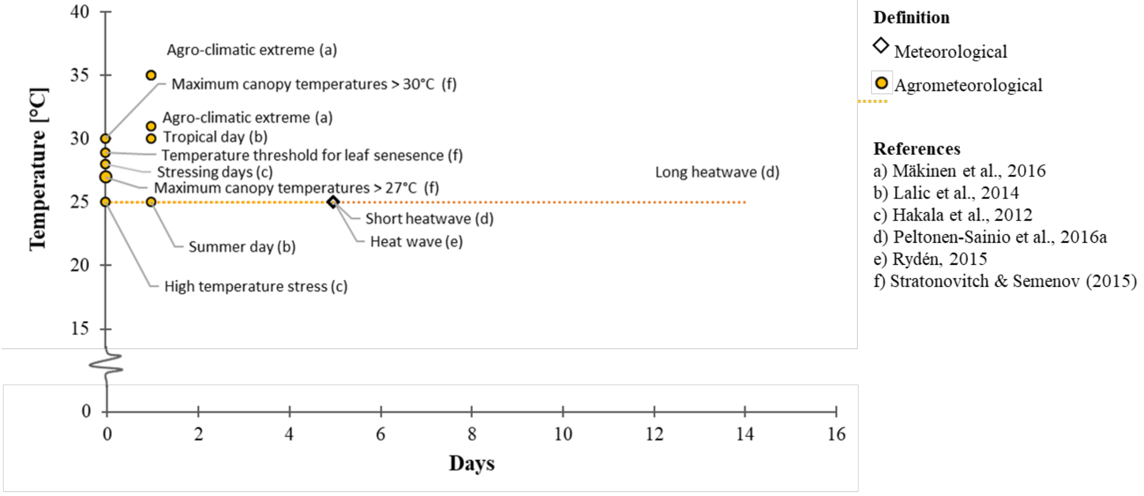
Figure 3. Visualization of definitions of start- and end of growth season, spring- and autumn

temperatures are ranging from 1°C (cereals & peas) up to 8 °C (potatoes) (Geisler 1983; Gunnarson 2012; Johnsson 2016) (Figure 3).

Autumn is defined as temperatures < 10°C during five consecutive days occurring after the 1st August. Winter is defined for temperatures < 0°C or for day length <9 h and decreasing earliest 2 weeks after start of autumn (Mattson et al. 2018). The meteorological end of the growing season is defined as the last day of four continuous days when daily average temperature is > 5 °C (SMHI n.d b). Other definitions are the first five consecutive days in autumn when average temperatures for the five-day period < 5 °C (Figure 3). This period is delayed if the 5-day period have had average temperatures > 0.0 °C, followed by two continuous five-day periods with $T_{average} \geq 5°C$ and that with the first five-day period have had a total average temperature $\geq 5°C$. (Johansson 1973). The period of non-frozen ground ends in autumn when daily average temperatures reach < 0.0 °C for five consecutive days, or when a developed snow-cover occurs (Johnsson, 1973/1974). However, vernalization starts already at higher temperatures, e.g. 10°C for winter wheat (Fowler & Limin 2004; Fowler et al. 2014) while the range can vary over a larger interval (-1.3 to 15.7°C) (Porter & Gawith 1999; Fowler 2008). Threshold temperatures for initializing vernalization varies within genotypes as well as within crop species. For example, Fowler (2008) showed an upper vernalization threshold from 9.3-17.2 °C for different winter wheat varieties and a threshold of up to 19.6 °C for winter rye, while Waalen et al., (2014) set a fixed vernalization temperature of 5°C for winter rapeseed.

Extreme heat

Heat stress affect plants in either indirect- or direct ways and the threshold temperatures for heat stress depends on plant development stage (e.g.Porter and Gawith, 1999; Wheeler et al., 2000). Belusic et al., (2019) recommended heatwaves and cold waves to be defined by thresholds of max-, min- or mean temperatures under a period of at least three consecutive days based on an average climate



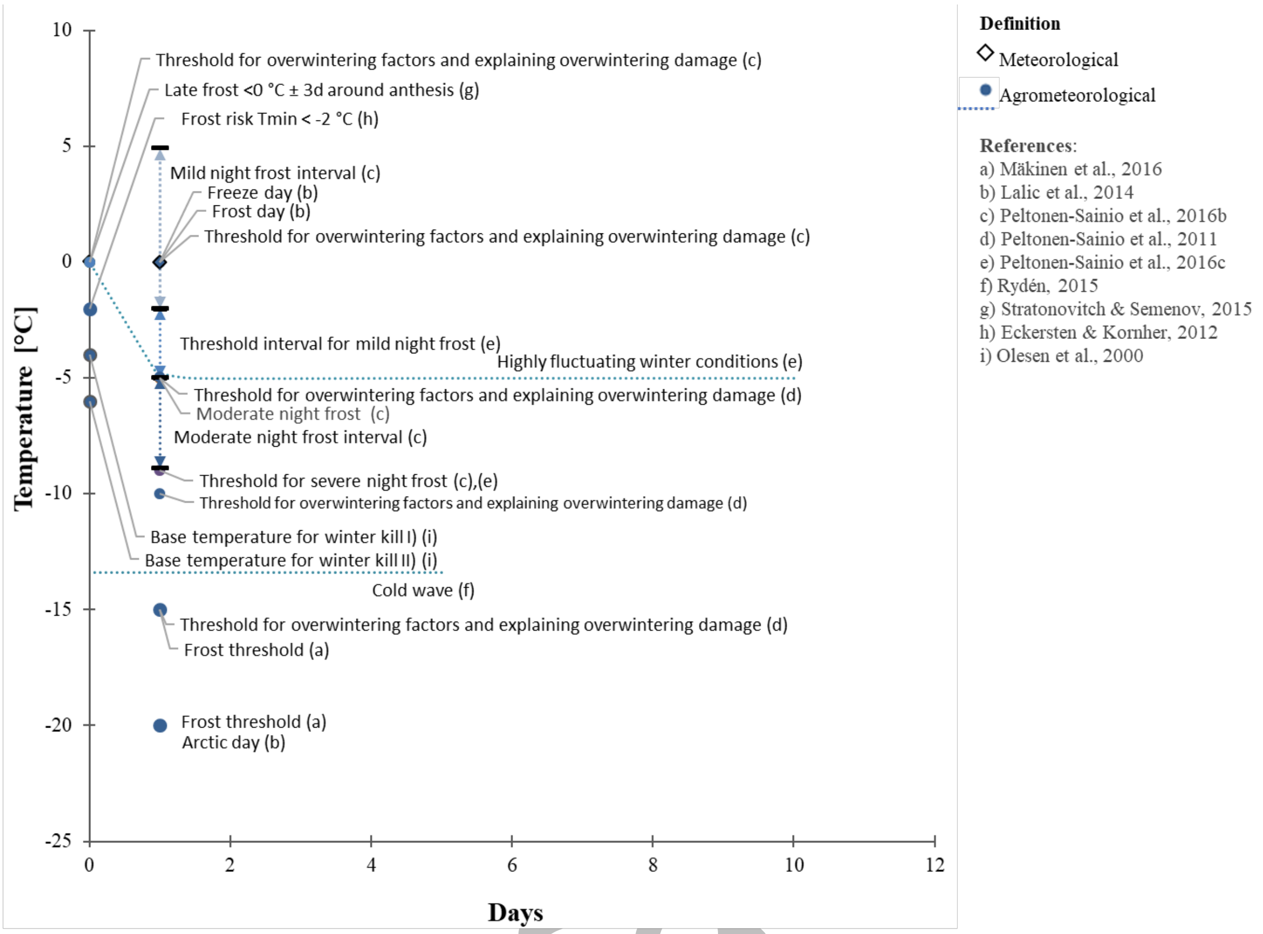
Agro-climatic extreme	Any day with Tmax 7 days before or 14 days after heading > 35°C OR any day with Tmax between heading and 10 days before maturity > 35°C; any day with Tmax 7 days before or 14 days after heading > 31°C
Tropical day	Any day with Tmax > 30°C
Summer day	Any day Tmax > 25 °C
Stressing day	Number of days with Tmax ≥ 28°C 1 week before to 2 weeks after heading
Short heatwave/Heatwave	heat ≥ 25°C lasting 5 days
Long heatwave	Heat lasting more than 14 days with less than 2 days with Tmax <25.1°C
High temperature stress	≥ 25°C one week before heading to up till two weeks after heading
Temperature threshold for leaf Senesence	≥ 28.93 °C
Maximum canopy temperatures	≥ 27°C reduces number of fertile grains per unit of ear dry mass for heat sensitive wheat varieties ≥ 30°C reduces potential grain weight for heat sensitive wheat varieties

Figure 4. Magnitude and temporal scale for extreme high temperature events in Nordic countries related to crop production. Full references are displayed in Table 3 in Appendix.

period. Heat has in literature from the Nordic countries and agricultural conditions been defined by threshold temperatures from 25 °C (*summer days*) (Hakala et al. 2012; Lalic et al. 2014; Peltonen-Sainio et al. 2016) up to 35 °C (Mäkinen et al. 2018). (Figure 4). These temperatures can be set in relation to optimal photosynthesis which due to light-saturation occurs around 20-35 °C for C3-crops and 30-40°C for C4-crops, while respiration increases with temperature and optimum photosynthesis processes occur at a threshold of around 40°C (Pittermann & Sage 2000; Sage 2002; Porter & Semenov 2005; Sage & Kubien 2007). Optimal temperature for C3, C4 and CAM-plants increase with growth temperature of the plants, while assimilation efficiency by photosynthesis over low- to high growth temperatures indicate relative stable performance for C3, increasing performance for C4 but reduced performance for CAM-plants (Yamori et al. 2014). C3 and C4 photosynthetic assimilation performance varies with temperature, where C3 crops has an advantage during low temperatures due to higher abundance of the enzyme Rubisco, which reach carbon saturation at lower carbon dioxide levels under lower temperatures. Yet the enzyme activity increases with increased temperatures up to optimum (Pittermann & Sage 2000). Theoretically, the energy-binding efficiency of incoming solar radiation is higher in C4 plants. Mainly due to reduced photorespiration favored by higher CO2 levels within the bundle-sheet cells. Yet this is mainly an advantage under higher temperature and lower atmospheric CO2 levels (Zhu et al. 2008; Sharwood et al. 2016).

Frost and freezing temperatures

Frost is defined as air temperatures ≤ 0 °C at 1.25-2.0 meters height measured inside a weather shelter (Snyder and de Melo-Abreu, 2005; SMHI, 2020f). Freezing temperatures are harmful to plant tissues due to potential formation of extracellular ice, which due to lower ice vapor pressure extract water from within cells, causing them to dehydrate. The severity of dehydration as well as critical temperatures for freezing depends on crop species, variety and their individual cell properties, hardiness, and phenological development stage (Snyder & de Melo-Abreu 2005; Waalen et al. 2014). Thresholds used in literature varies from individual days of temperatures below < 0 °C down to arctic days -20 °C. Longer periods of cold waves have been defined as temperatures <13.4°C for 5 continuous days, based on the 5th percentile of 30-year weather period (1961-1990 in Uppsala) (Rydén 2015) (Figure 5). Air temperatures < -10°C are classified as damaging, and air temperatures < 20°C as possible to cause loss of winter crops (Das et al. 2003). The harmful effect on plants related to cold temperatures is not only dependent on magnitude but also related to, crop species, variety vernalization period and winter dormancy (e.g. (Porter & Gawith 1999; Waalen et al. 2014; Bergjord Olsen et al. 2018) or during spring when plant growth has been initiated.



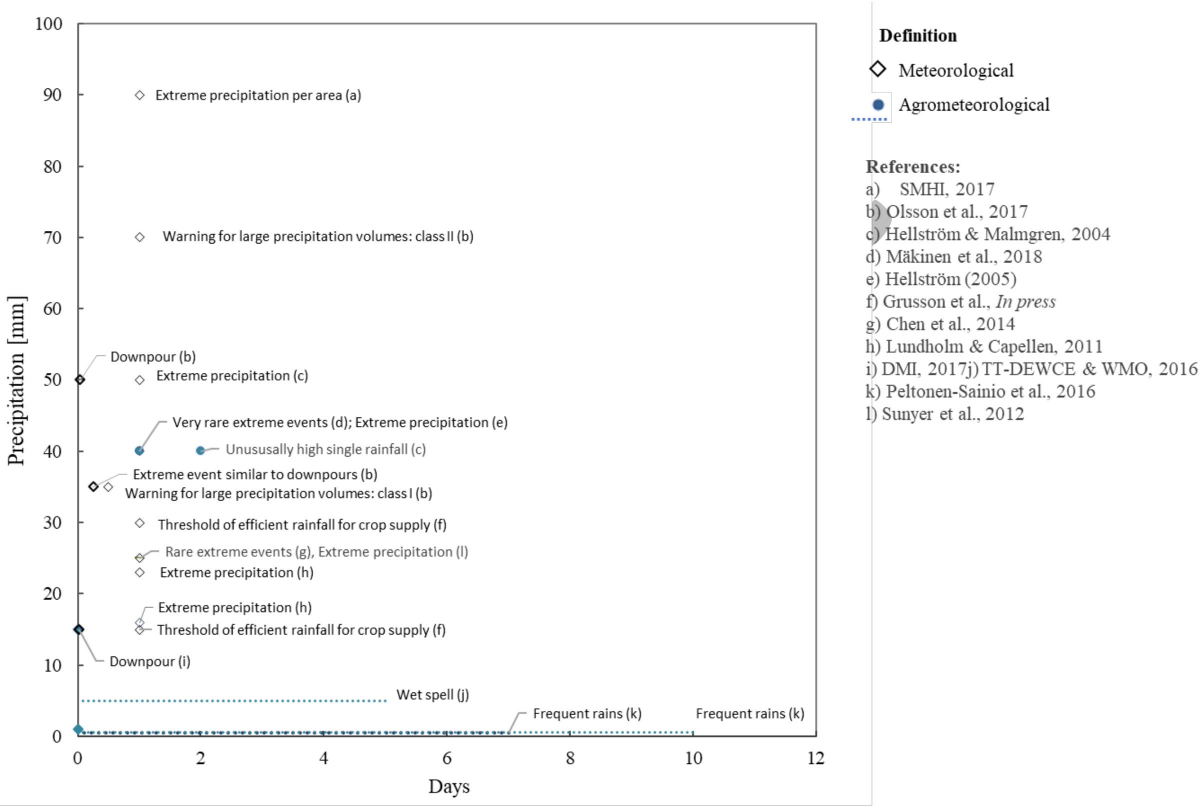
Threshold for overwintering	Sum of daily Tmean < 0 °C
Mild night frost interval	Tnight 4.9 °C to -2 °C
Freeze day	Freeze day Tmax < 0.0 °C
Frost day	Frost day Tmin < 0.0 °C
Threshold interval for mild night frost	Tnight -2 to -5 °C
Highly fluctuating winter conditions	Temperatures Tmax > 0°C followed by a period of ≥ 10 days with Tmean < -5 °C
Threshold for frost	Tmean ≤ -5 °C
Moderate night frost interval	Tnight -5 °C to -8,9 °C
Cold wave	Cold wave: -13.4°C for at least 5 consequtive days
Frost threshold	Any day with Tmin < -15 °C **OR** any day with Tmin < -20°C
Arctic day	Arctic day Tmin < -20 °C
Late frost	Tmin canopy < 0 °C ± 3 days around anthesis
Frost risk	Tmin < -2 °C
Base temperature for winterkill	I) Tbase < -4 °C before two phyllochrones after formation of flag leaf primordium in winter wheat II) Tbase < -6 °C after two phyllochrones after formation of flag leaf primordium in winter wheat

Figure 5. Magnitude and temporal scale for extreme low temperature events in Nordic countries related to crop production. Full references are displayed in Table 4 in Appendix

Rainfall and precipitation

High precipitation included in this review is mainly defined by meteorological measures, defined differently in magnitude depending on duration (Figure 6). An important aspect of extreme cases of both too much and too little rainfall is that despite the influence on agricultural production, the extreme variable is essentially meteorological and often reliant on the reference period of average normal precipitation (standard of 30yrs) used by meteorologist.

Definitions range from *frequent rains* – defined as 7 days, where rainfall exceeds 0.5 mm within 2 weeks and < 2 successive rainless days (< 0.5 mm) with accumulated precipitation for the 2 weeks higher than monthly mean precipitation. Another definition is 10 days with rain during 3 weeks, with the accumulated precipitation being 50 % higher than the monthly average precipitation (Peltonen-Sainio et al. 2016). On the other end, *extreme precipitation* for Sweden has been defined as 90 mm d^{-1} per 1000 m^2 (SMHI 2017) or volumes up to 70 mm d^{-1} for warnings of large precipitation volumes (Olsson et al. 2017). *Excessive rainfall* in direct relation to agriculture has been defined as more than 60 days with water saturation at field capacity (Mäkinen et al. 2018). Wet spells are defined as >1mm precipitation per day over >5 consecutive days (TT-DEWCE WMO, 2016). The same volumetric threshold is used by Breinl et al., (2020) and Zolina et al., (2013) yet without any threshold on the duration (Figure 6). An example of extreme indices based on percental deviation from normal precipitation was used by Nkurunziza et al. (2015). They impartially linked yield deviations to significant precipitation deviations (± 30 % from normal precipitation) in four long-term experiments



Extreme precipitation per area	> 90mm d^{-1} 1000m^{-2}
Warning for large precipitation volumes:	**Class II:** > 70 mm 24 h^{-1} **Class I:** > 35mm 12h^{-1}
Downpour	≥ 50 mm h^{-1} **OR** ≥ 1 mm min^{-1} **OR** ≥ 15 mm 15 min^{-1} **OR** ≥ 15 mm 30 min^{-1}
Extreme precipitation	≥ 50 mm d^{-1} **OR** ≥ 25 mm d^{-1} **OR** ≥ 50 mm d^{-1} **OR** ≥ 40 mm d^{-1}
Very rare extreme event	≥ 40 mm d^{-1}
Unusually high single rainfall	≥ 40 mm 48 h^{-1}
Extreme event similar to downpours	≥ 40 mm 6 h^{-1}
Threshold of efficient rainfall for crop supply	15 mm d^{-1} **OR** > 30 mm d^{-1}
Rare extreme events	≥ 25 mm d^{-1}
Wet spell	Five consecutive days with precipitation > 1mm d^{-1}
Frequent rains	Seven days with rainfall ≥ 0.5 mm per day within 2 weeks, ≤ 2 successive rainless days <0.5 mm per day with accumulated precipitation ≥ monthly mean precipitation for the two-week period **OR** ≥ 10 rainy days within a three week period, ≤ 2 successive rainless days and accumulated precipitation for 3 week period ≥ 150% of the monthly mean precipitation.

Figure 6. Magnitude and temporal scale for defining extreme precipitation events in Nordic countries related to crop production. Full references are displayed in Table 4 in Appendix.

in Sweden. They explicitly present years where precipitation deviations coincided with yield losses of 30 %, 50 % and 70% (Nkurunziza et al. 2015).

Soil saturation and flooding

Water is a main parameter globally, limiting yields in rainfed systems due to crop requirement of timely water supply of accurate magnitude in order to maintain e.g. metabolic processes, including photosynthesis, solute transport, transpiration and ensure nutrient uptake from the soil. Soil saturation or ponding of water in the unsaturated zone is a time limited agrological hazard due to high waterflow, snowmelt or high precipitation events, while flooding is a hazard from a landscape perspective with overflow of areas normally not situated under water (e.g. (UN). Too little water will limit these processes while too much water limits available oxygen for respiration processes to harmfully low levels, defined to 0.05-0.10 m^3 m^{-3} as a critical lower limit for soil aeration for plants (Håkansson et al. 2002, 2011; Lipiec & Hatano 2003; Wesström et al. 2016). Root growth can generally recover from soil saturation duration < 3 days. Yet impacts of soil saturation is also dependent on development stage, crop species and other weather parameters (Malik et al. 2002; Wesström et al. 2016).

The placement of the seed at sowing is less important in soils with good water holding capacity and high volume of plant available water (Håkansson et al. 2011). The optimal threshold of 10 % air-filled porosity in soils depends on water content, soil texture and degree of compactness[2] (D). A threshold of 10 % air-filled porosity in a majority of soils occur under water content 10 kPa and D < 87, while higher D increase tension for root penetration and decrease soil-oxygen levels (Håkansson & Lipiec 2000).

Furthermore, sufficient water levels affect the workability and buoyancy of arable lands for land preparation before- and during the growth season. Too dry land reduces the possibility to achieve a good sowing bed. Excess soil water can in contrast negatively affect soil structure by crumbling or dispersion and thus affect pore size and pore size distribution (e.g. Wesström et al., 2016). Excess soil water furthermore reduce buoyancy of soils to machine operations which affects seedbed preparation and optimal soil aeration and compaction (e.g. Obour et al., 2018). Optimal soil moisture for tillage (Θ_{OPT}) can be set to the water content when soil textural pores are mainly water filled, while structural pores in between aggregates are drained (Obour et al. 2019a). The range of optimal soil moisture has been determined to 0.7-0.9 Θ_{PL} where Θ_{PL} is the plastic limit (Keller et al. 2007); 0.8 -0.9 Θ_{PL} (Arvidsson & Bölenius 2006) and 0.9 Θ_{PL} (Dexter & Bird 2001). The workable range for tillage has shown to be reduced with lower soil organic carbon content and higher clay content (Dexter & Bird 2001; Obour et al. 2019a). Water content for wet- and dry tillage potentially increases while the range of workable water content decreases with increased clay content (Obour et al., 2019b). The range of workable water content (between -65 to -1800 hPa and -3600 to -4100 hPa) has been found to be positively related to volume of pores > 30 µm, i.e. air-filled pores (Obour et al., 2019b). Additionally, a lower clay content of 10% in order for soils to be plastic has been estimated by Keller and Dexter, (2012). Yet, considering other literature, the plastic limit might be lower due to the content of organic matter. Dexter and Bird, (2001) has defined the lower dry limit of water content for tillage as:

"…the water content at which the strength of the soil is twice the strength at the optimum water content." (p. 207, Dexter and Bird, 2001)

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[2] Degree of compactness is defined as *"…the dry bulk density of the same soil obtained by a standardized, long-term uniaxial compression test at a stress of 200kPa."* (p. 72) (Håkansson & Lipiec 2000).

An example of applied limitations to harvest and sowing is used by Trnka et al.(2011), studying effects of climate change on crop yield throughout Europe. The authors set the threshold of maximum soil water content in top 0.1 m soil layer to > 10 % and < 70 % for suitable days of harvesting and sowing. Yet combined with an average daily temperature > 5 °C and ≤ 1mm precipitation the same day and ≤ 5mm preceding day (Trnka et al. 2011).

Additionally to effects on yield and workability, soil water levels are important as the share of air-filled pores affects microbial activity. This determines the cycling of nutrients in the soil, indirectly affecting crop growth. A water content in the range of 0.3-0.6 m^3 m^{-3} will lead to the highest microbial activity with increasing nitrification rates up to 0.6 m^3 m^{-3} (Wesström et al. 2016).

Heavy precipitation and flooding from an agrometeorological perspective is a cause of temporal interacting factors and can have several direct and indirect impacts related to agricultural production (Das et al., 2003, p. 83). In this review I have limited focus to direct implications towards crop yield. Flooding is defined as an event when an area that normally is above the level of watercourses, water bodies or sea level gets covered by water (European Parliament and the Council 2007). An evaluation of the efficiency of different water retention measures from United Kingdom classified floods as *"small"* if the flood event have a return period < 10 years and the chance of exceeding the magnitude in any year is a chance of 10%. Medium flood events where classified as return period between 10-100 years with 1-10% change of being exceeded in any year. Large flood events where classified for a return period >100 year with less than 1% change of being of higher magnitude in any of the years (Burgess-Gamble et al. 2017).

Flooding linked to agriculture can be classified as an event that covers a terrestrial area that is normally not under water. This can be due to high water levels from water bodies/water courses or due to high precipitation events, melting water or groundwater. Furthermore, the impact area can be defined as *primary* – the area directly flooded by the excess water, and *secondary* – and area which draining capacity gets limited by the flooded primary area. Thus, the secondary area becomes saturated (Enghang et al. 2016; Wallentin et al. 2016). A flooding event can additionally be short-term, classified as

> *"An elevated water level resulting in fully saturated soil conditions during 1-3 days before the soil can be drained to drainage equilibrium"*(Enghang et al., 2016 p.4), or long-term, classified as "*An elevated water level resulting in fully saturated soil conditions during 1-2 weeks before the soil can be drained to drainage equilibrium.*" (Enghang et al., 2016, p.5).

An example from UK compared impact of flooded areas by comparing water columns over- and under the threshold of 0.3m (Harvey et al. 2019).

In addition to duration, occurrence frequency of flood events and volume that exceeds draining capacity – the area cover of a flooding event is important. It is a direct measure of impact severity on the surrounding area. Swedish guidelines for evaluating flood risks are based on return frequency of extreme flows, e.g. 100- or 200yr occurrence (Myndigheten för samhällsskydd och beredskap, 2014). Areas under major risks of flooding (*betydande översvämningsrisk*) has been defined based on societal factors linked to urban areas/infrastructure, health, economy and environment, and account for historical flood occurrence. Environmental risks includes protected nature areas and contaminated areas prone to leaching. (Myndigheten för samhällsskydd och beredskap 2018). The inclusion of areas for major risk for flooding does not include a definition for agriculture. Yet, this can be related to the definition of major impact on agricultural land (Edström & Karlsson 2019). This is defined from available farmland in excess to required area to sustain yearly added growth value, in order to fulfill the national food strategy. The excess land for additional growth is expected to be available for development of increased water management in the arable landscape. This area has been estimated to a reduction of 5000-12000 ha over a period of six year and regarded as a permanent loss of arable land. Flooded ground will on the other hand be partially usable during the year. Yet for individual years with more severe flooding, this estimated loss of area can possibly be used as a benchmark for Swedish conditions and flooding severity, with flood events affecting more than the threshold of 5000-12000 ha having hazardous impact on national food production.

Drought and dryspells

Agricultural drought is emanating from lack of precipitation, interlinked with meteorological circumstances as well as soil properties, -physical conditions and -biological factors (Wilhite & Glantz 1985; Destouni & Verrot 2014). World Meteorological Organization defines drought as water shortage for life supporting requirements, with severity of agricultural drought defined by the impact on crop growth. Depending on the weather patterns in different climate zones and if the considered area is naturally humid or dry, drought is defined differently with shorter or longer periods without water (WMO 2010). One way of defining agricultural drought is the threshold of relative evapotranspiration (R_{ET}) defined as the ratio between ET_a and ET_P. Drought has been defined as starting from $R_{ET} < 1.0$ with varying stages of water deficit, in between, to severe drought when $R_{ET} < 0.15$ (e.g. (Johnsson 1972; Mogensen et al. 1996, 1997; Trnka et al. 2011; Rötter et al. 2013; Lalic et al. 2014; Mäkinen et al. 2018) (Figure 7).

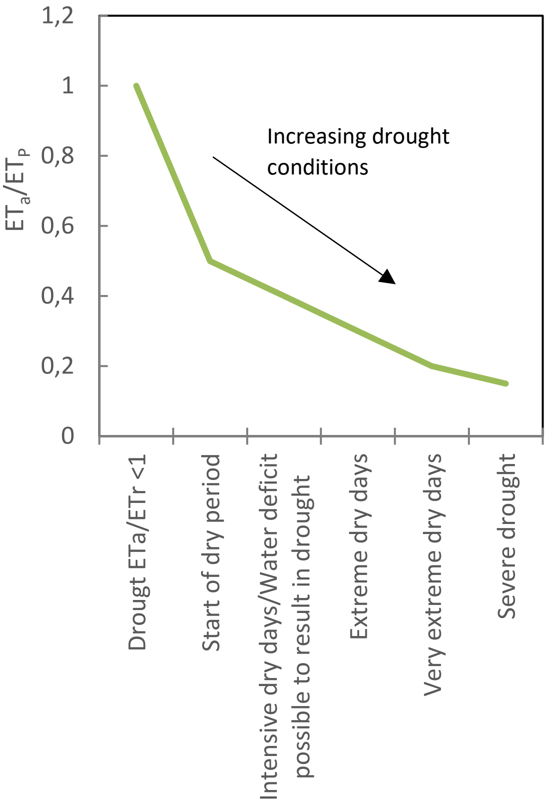
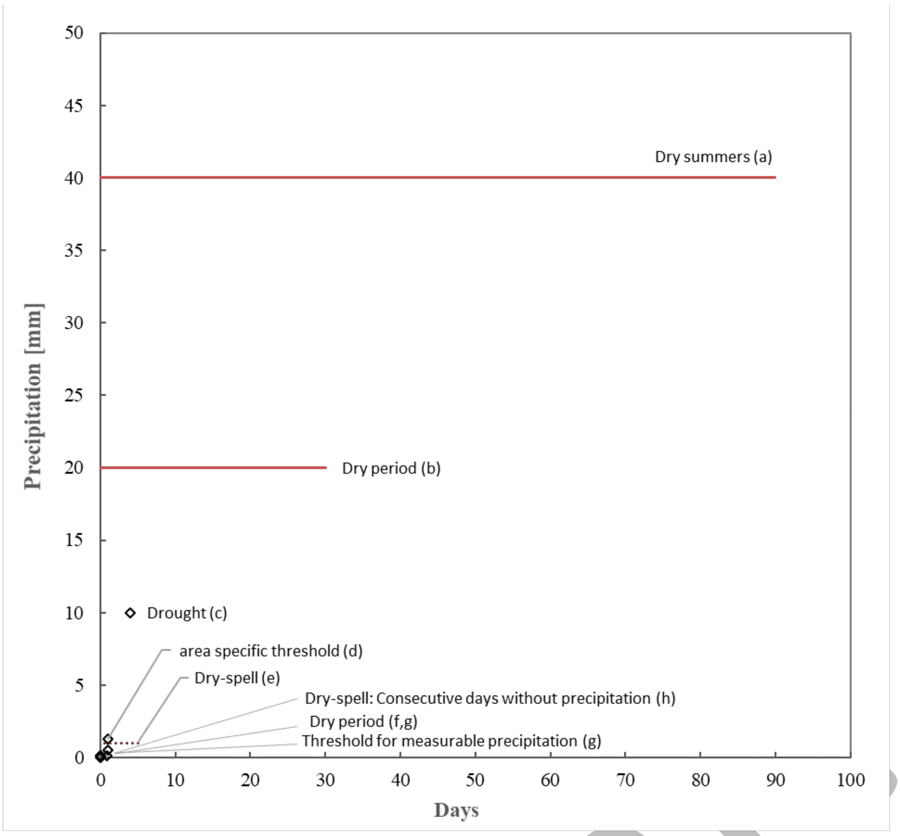


Figure 7. Thresholds for drought conditions defined by the ratio of actual evapotranspiration (ET_a) and potential evapotranspiration (ET_P).



References:
a) Johnsson, 1972
b) de Toro et al., 2015
c) Peltonen-Sainio et al., 2016b
d) Bärring et al., 2006
e) TT-DEWCE & WMO, 2016
f) SMHI, 2018
g) Stensen et al, 2019
h)Persson & Höglind, 2015

Dry summers	Between may-june P < 40 mm
Dry period	Period of continuous absence of measurable precipitation, i.e. < 0.1mm
Drought	Total precipitation <10mm and no more than 4 days rainfall during a 14-days period
Area specific threshold	0.48 mm d^{-1}
Dry spell	At least 5 consecutive days with Pday < 1 mm
Dry period	Period of continuous absence of measurable precipitation, i.e. < 0.1mm **OR** ≤ 20mm over 30 days
Threshold for measurable precipitation	Long and continuous period missing measurable precipitation, < 0.1mm

Figure 8 . Magnitude and temporal scale for defining drought events in Nordic countries related to crop production. Full references are displayed in Table 4 in Appendix

Meteorological dry-periods have been defined as precipitation < 0.1mm (Breinl et al. 2020) and < 0 mm d^{-1} i.e. no reported precipitation (Zolina et al. 2013) or as a period with less precipitation than normal (related to a reference period) (Salomon et al. 2019). The threshold for drought is often classified as < 1 mm d^{-1} (Bärring et al. 2006; TT-DEWCE WMO 2016) or < 0.1 mm d^{-1} (Bärring et al. 2006; SMHI 2018; Stensen et al. 2019; Breinl et al. 2020) of which the latter is classed as the limit for measurable precipitation. Droughts of longer duration has been classified as *dry summers* (< 40 mm between May-June (Johnsson 1972), as < 20 mm over 3 months (de Toro et al. 2015) or as total precipitation < 10 mm with < 4 days of rainfall during 2 weeks (Peltonen-Sainio et al. 2016) (Figure 8)

Two commonly used measures for drought analyses are the indices SPI (Standardized Precipitation Index) and SPEI (Standardized Precipitation Evapotranspiration Index). The Standardized Precipitation Index (SPI) characterize drought and extreme precipitation in relation to the median value of long-term precipitation data (preferably 30 year). The observed data is fitted to a probability function that is converted to a normal distribution. The index is valued on a scale where negative SPI-values < -1.0 indicate the start of a drought, while a change to positive SPI values indicate finalized drought. Events wetter than normal are considered from SPI ≥ 1.0. Extremely wet and extremely dry events are considered when SPI is > 2.0 or < -2.0 respectively. (TT-DEWCE & WMO, 2016.). SPI can be estimated for different temporal scales due to different response time of drought or wet event impact on different hydrological storages. Soil moisture is e.g. affected on short temporal scale, while river discharge, aquifers and larger water bodies on landscape scale are affected over a longer period (World Meteorological Organization, 2012). SPI only considers precipitation for determination of drought. However, there is an important issue of additionally including temperature as a parameter affecting drought conditions and water requirements for crop production. The Standard Precipitation Evapotranspiration Index (SPEI) is based on SPI and similarly a standardized probability measure. Yet SPEI additionally include temperature as a parameter by estimating the probability of water deficiency for potential evapotranspiration (Vicente-Serrano et al. 2010)

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There are several other measures available for drought of various complexity due to required input data. For further description of additional indices see e.g. Svoboda et al. (2016).

An interesting example of definition due to standard-deviations, was done by Li et al., (2019) who estimated impact of extreme drought and -precipitation on maize yield in USA. They defined a standardized anomaly (γ) as:

[1] $\gamma = (\gamma_t - \gamma)/\sigma$ Li et al., (2019)

Where γ_t is the departure of climate for year *t*, $\overline{\gamma}$ is annual mean state over a reference period and σ is the standard deviation. Extreme drought was defined as anomalies of precipitation < -2 σ and >+3.5 σ; moderate drought and moderate excessive rainfall by anomalies >-2 σ and <+2.5 σ; extreme heat and cold as anomalies >+2.5σ and <-2σ respectively. Yet, the authors notify that these definitions where still based on meteorological events and that synergetic effect from e.g. soil parameters, pests, nutrient cycling, and management strategies where not accounted for.

Discussion

Several definitions of extreme weather are used for Swedish agricultural purposes. Yet there seem to be missing variables and indices related to threshold for crop growth and –development and not presenting any principal standard from an agrometeorological perspective. Especially related to impact on soil moisture and evapotranspiration associated with critical temperatures, high precipitation and water ponding. Few definitions included duration of temperature thresholds, which is also an important aspect of crop damage, as both short shock events and events of longer duration can have negative impact directly and indirectly through impact on water availability. As different tolerance towards both high- and low temperatures varies between crop, cultivars and phenological stage, these magnitude thresholds naturally varies in literature when describing temperature. One index that was not brought up during this review is the temperature sum, which is important when discussing the phenological development of crops. With warmer temperatures, the sowing period has already been monitored to occur earlier than historically (e.g. Peltonen-Sainio and Jauhiainen, 2014) . Increasing temperatures can possibly speed up growth and development of agricultural crops, shortening the overall period between sowing and harvest (Olesen et al. 2012; Peltonen-Sainio & Jauhiainen 2014). However, the theoretical sowing date is not a guarantee for earlier sowing in practicality as suitability for sowing is also dependent on the practical possibility for sowing operations related to soil moisture and –structure (e.g. van Oort et al., 2012; Section 4.1.5). Additionally elevated temperatures might lead to a shift in advantage for introducing more C4 crops in the crop rotations in Nordic countries, due to their photosynthetic advantage during elevated temperatures. Although, this is discussable in relation to how much temperature is expected to increase, as well as CO2 elevation due to the relative stability of C3-crop performance under elevation of CO2-concentrations.

Extreme precipitation linked to agriculture has mainly been defined by meteorological definitions, missing the important factor of impact on soil saturation and lacking consistency. Extreme precipitation can have direct negative impact by causing mechanical damage on crops. This factor was not found in the reviewed literature but of relevance especially in plant breeding for increased resistant towards mechanical impacts. In addition, dryspell and drought definitions has mainly been linked to meteorological definitions of periods without precipitation. However, agrometeorological drought seem to be more clearly defined compared to water ponding, with several definitions available. By e.g. declining soil moisture, relative evapotranspiration or by globally adjusted drought indices that include soil moisture deficits and evapotranspiration effects (see e.g. Destouni and Verrot, 2014; Mishra and Singh, 2010). or for a period of precipitation that does not fulfill crop water demands (e.g. de Toro et al., 2015). Compared to Nordic countries where temperature is limiting for crop growth, precipitation is more commonly used as measure for crop growth potential in other climate zones with distinct rain- and dry periods. If temperature enables earlier sowing however (compared to definitions in e.g. section *4.1.1 Start- end and duration of cropping season and sowing conditions*), it also put a requirement on the timeliness of fulfilling precipitation requirements i.e. as sowing possibly might rather be limited by precipitation, either too much or too little for sowing operations and germination. Thus, to explore future possibilities and limitations of weather impact on increased potential for Nordic crop production, synergetic development of timed limitations of temperature and precipitation needs to be further assessed, which is linked to crop water availability and circulation from a systemic perspective.

This context open up for more unified agrometeorological definitions linked to heavy precipitation to account for soil saturation and flooding of arable land. A direct effect of preceding soil moisture levels and soil properties. Including soil moisture and especially soil saturation into extreme weather definitions is though more complex than the meteorological definition of heavy precipitation, as water ponding also depend on evapotranspiration and infiltration capacity. These parameters are consecutively dependent on temperature, soil and crop properties. This review shows that there is missing a synthesis with basis in essential thresholds for crop production, especially considering intra-annual threshold of magnitude and duration, depending on crop development stage for both high- and low temperatures and droughts/dryspells linked to development stage and soil moisture levels. The usefulness of extremes indices varies with context, which is also reflected in the lack of a unified view. However, in order to compare results between studies and to deliver a unified view from academia to the wider community, at least a unified view on the level of extreme should be agreed. Focusing on the agrometeorological perspective it is also essential to identify its hierarchical dependence on preceding meteorological or hydrological events. Additionally, a clear view that severity in agriculture does not necessarily require a meteorological or hydrological extreme to occur is required (see section 2). Defining thresholds with hazardous implications for specified crops, creates a linkage between magnitude distribution and absolute threshold. Meteorological events (both single and compounded) leading to events that surpass the agrometeorological thresholds can then be evaluated, mitigated or adapted for. However, this leads to the challenge to first define the acceptable level of impact in agriculture. A good start linked to soil moisture that can be adapted to site-specific properties is the definition of short- and long flooding events by Enghang et al., (2016). The reviewed literature did not include any agrometeorological threshold of extreme flooding that includes the area extent of the event linked to agricultural impact. The Swedish Civil Contingencies Agency (MSB) uses a continuous grading of the possible larger societal/economic impact due to larger flooding area. This can be adapted to agriculture as well with a more extreme event with higher negative yield impact. However, a defined threshold level of "acceptable" crop damage (e.g. Edström and Karlsson, 2019) is possibly required working backward from tolerable impact to what is considered as an extreme event. Yet impact and financial costs due to flooding depends on which stage during the growing season that the extreme event occur, due to possibilities of re-sowing or previously costs for measures as fertilizing, seeds or pesticide applications (Enghag et al. 2016).

Conclusions

It is clear that what is considered and extreme event does not have one simple definition, but is dependent on the sector, region and for the context where the definition should be used for. However, due to known limitations of cropping systems to certain threshold related to weather parameters, it would be beneficial to agree on common response variables in cropping systems. This would assist in agreeing on standard approaches of extreme weather from an agrometeorological lense. Possibly this can be combined with meteorological definitions in order to account for crop yield impacts, as well as give statistical measures on severity and temporal occurrence. One example is by e.g. combining agricultural thresholds with statistical return periods of meteorological- and hydrological events. Yet, most important in order to communicate potential and limitations to results on extreme weather related impact on crop yield is for the scientific community to more clearly state their definitions and what it is based on, in their publications. This would enable easier comparisons between results from different research efforts and increase the unified picture of how weather related events affect crop production.

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Appendix

Table 3. Definitions of extreme weather events adapted from World Meteorological Organization (TT-DEWCE WMO, 2016) and the Expert Team on Climate Change Detection and Indices (Zwiers and Zhang, 2009)

Event	Definition	Reference
Extreme weather	*"The occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable. In many cases, a weather or climate event with high impact is also deemed as extreme event"* (p.6)	TT-DEWCE WMO (2016)
Drought	*"A marked unusual period of abnormally dry weather characterized by prolonged deficiency below a certain threshold of precipitation over a large area and persisting for timescale longer than a month".* (p. 25).	
Dryspell	*"A period of* ***unusually*** *dry conditions (*) of at least five*[1] *consecutive days with daily precipitation less than 1mm.* *(*) i.e. to exclude usually dry periods, such as during dry seasons."* (p. 25)	
Extreme precipitation	*"A marked precipitation event occurring during a period of time of 1h, 3h, 6h, 12h, 24h or 48hours with a total precipitation exceeding a certain threshold defined for a given location."* (p. 19).	
Wet spell	*"A period of at least five*[1] *consecutive days with daily precipitation exceeding 1 millimeter"* (p.19)	
Heat waves	*"A marked unusual hot weather (Max, Min and daily average) over a region persisting at least two consecutive days during the hot period of the year based on local climatological conditions, with thermal conditions recorded above given thresholds" (p. 10).*	
Cold waves	"*A marked and unusual cold weather characterized by a sharp and significant drop of air temperatures near the surface (Max, Min and daily average) over a large area and persisting below certain thresholds for at least two consecutive days during the cold season."* (p.15).	
Heavy precipitation days	Number of days where Pday > 10 mm d-1	(Zwiers & Zhang 2009).
very heavy precipitation days	Number of days where Pday > 20 mm d-1	
very wet days	> 95th percentile of precipitation on wet days* *consecutive days with P > 1mm	
extremely wet days	Days with precipitation > 99th percentile based on the reference period 1961-1990	
Frost days	Daily minimum temperature < 0°C	
Icing days	daily maximum temperature < 0°C	
cold nights	Daily minimum temperature < 10th percentile of base period 1961-1990	
cold day-times	Daily maximum temperatures < 10th percentile of the base period 1961-1990	

[1] The range of five days is set to harmonize with a measure by the Expert Team on Climate Change Detection and indices (ETCCDI) and Indices for monthly maximum precipitation where a five-day interval is used. However, the initial definition from WMO (World Meteorological Organization 1992) did not include a specific number of days, nor a certain water volume.

Table 4. Reviewed references for defining thresholds of extreme precipitation, -temperatures and drought

	References for quantitative extreme weather measures
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