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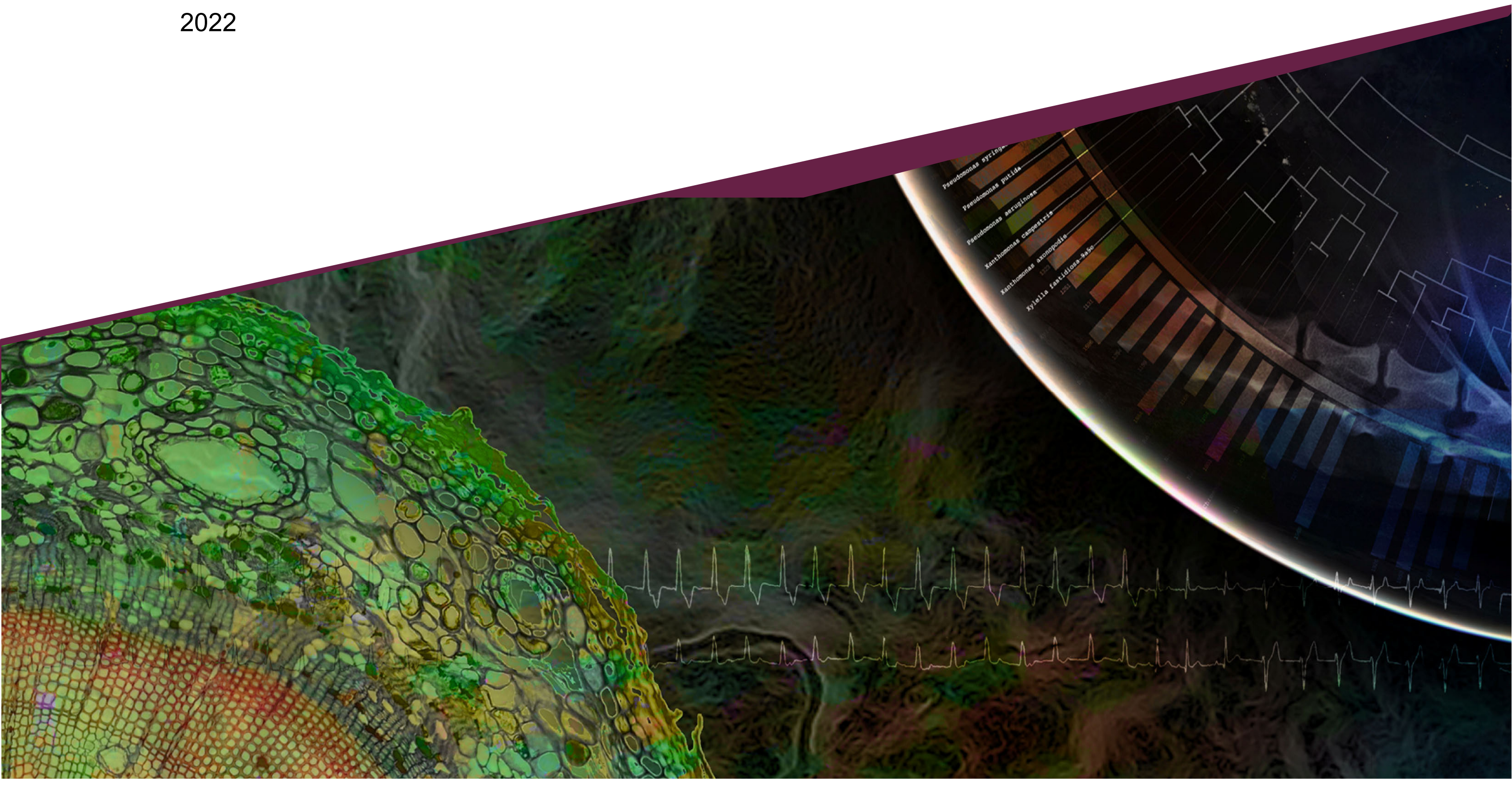

Identification and synthesis of agrometeorological extreme weather indicators for the temperate boreal zone

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Abstract

Extreme weather events are per definition rare. These events are classified differently depending on sector and system of interest. Agrometeorological extremes consider the relation of potential and actual impact of weather events on crop development and yield. Climate change is changing todays' extreme events in frequency, occurrence, and extent (intensity).

This document reviews definitions of extreme weather linked to agricultural production in the Nordics. The objective is to identify relevant agrometeorological indices of normal and extreme weather for assessing potential impacts on crop production in the temperate-boreal zone. The review is limited to indices related to the meteorological variables of precipitation and temperature.

The result show that definitions of agrometeorological extreme events used in literature are not standardized. The review found a substantial number of studies using typical meteorological definitions, especially linked to extreme precipitation and drought events (n =19 of 22, and n = 9 of 13 individual definitions respectively), even when the application was intended to assess potential agricultural (crop) impacts. In total, n = 33 publications for Nordic and global sources were reviewed with 44 % of definitions addressed temperature, 40 % addresses precipitation and 14 % related to combination of two or more c weather features (such as aridity index).

Unlike meteorological and hydrological indices, agrometeorological indices need to reflect intra-seasonal frequency and intensity of events, to inform crop and animal husbandry management. Relevant high-resolution agro-climatic assessments is necessary to inform agricultural adaptation strategies and investments in temperate-boreal zones, when todays' extreme weather becomes the new normal.

Contents

1. Background

Plant growth and -development is dependent on climatic conditions, synergetic effects of daily fluctuations in weather parameters, as well as synergetic effects of consecutive weather events. Farming systems require management to build resilience and ensure productivity for variability in weather events impacting crops - directly and indirectly - by effects on plant-soil-microbe interactions (e.g. Jia et al. 2019). Whether weather patterns and specified weather events can be classified as extreme is a matter of definition, and depends on the impact 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 last four decades have been consecutively warmer (Gulev et al. In press) and the last six-year period (2015-2020) have been the warmest since the mid-19th century (World Meteorological Organization 2021b). Additionally, new projections suggests that there is a 40 - 60% change that global average temperatures rises above 1.5 °C[1] during any individual year during the period 2021-2025 (2030) (World Meteorological Organization 2021a; Lee et al. In press) and *very likely-* to *more likely than not* that the 1.5 °C global average temperature increase occur during the period 2021-2040 (Lee et al. In press). Global warming have potential to affect a range of large scale circulating systems (e.g. Lenton et al. 2019). Projected higher temperature imply shifts in precipitation and soil moisture of varying magnitude depending on region. It is expected that with every increase in temperature, events of hot temperature will increase in both magnitude and frequency, while heavy precipitation events and dryspell/drought events are projected to increase in magnitude per event (IPCC 2021b). Alterations in mean, variance and distribution of regional weather events (Seneviratne et al. 2012) are of great importance for crop production systems. New evidence show these new normal in weather will negatively affect yield potential and actual yields globally (Pörtner et al. In Press) and regionally (e.g. Bednar Friedl et al. In Press).

Projected effects of climate change on crop production indicate that the Nordic countries will experience relatively less temperature increase and precipitation increase, compared to central and southern Europe (Pörtner et al. In Press). Elevated temperatures and thus longer theoretical growth period has been brought up as a partly positive aspect in the Nordic region (Olesen et al. 2012a; Peltonen-Sainio & Jauhiainen 2014; Juhola et al. 2017). However interactions between parameters as dry periods and elevated temperatures might reinforce each other, limiting the potential of longer growth period (Trnka et al. 2011; King et al. 2018). Yield reduction and synergetic effects of weather events might be possible to adapt for, by considering maturing of crop species and choice of crop 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 towards weather related disturbances, the extreme impact on the system must be defined.

The term *extreme* can be related to either the event itself, the potential hazard, the final impact caused by an individual event, or temporally and/or spatially combined event(s) (Zscheischler et al. 2020). *Agro-meteorological extremes* comprise the relation of weather impact (direct- and indirect) on crop yield and related requirements on conditions for crop production (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 events is defined by thresholds based on observed distributions, various indices, or its impact on important sectors or parameters (Seneviratne et al. 2012; TT-DEWCE WMO 2016). . The extreme thresholds are based on historical data, including statistically rare values or events resulting in

[1] 1.5°C is the aimed upper limit of global average temperature increase set by the Paris Agreement, i.e. well below 2°C since prehistoric times) (United Nations Framework Convention on Climate Change 2016).

negative impact for one or multiple sectors (TT-DEWCE WMO 2016). Extreme events can furthermore be defined by statistical frequencies (often < 10th and > 90th percentiles of a dataset or defined return periods, as well as even lower limits (> 70th percentile) (Bärring et al. 2006; Fleig et al. 2011). The relevance of a definition varies depending on field and purpose (McPhillips et al. 2018). Some definitions might also be problematic with a transition of distributions in weather patterns (Harrington & Otto 2018): Depending on context, climate change and extreme weather indices can be set based on application or be set differently between locations (ETCCDI 2020).

Due to the vast variation in ways of defining extreme events, this document is a synthesis to explore quantitative definitions of extreme weather linked to agro-meteorology and agricultural production in the temperate boreal zone of Nordic countries. The synthesis will serve as reference further research projects linked to agriculture, in choosing a suitable definition of extreme events relevant for their research questions and studied agricultural system. The objective is to answer how extreme weather related to precipitation and temperature variations is defined and quantified for impacts on crop production in the temperate-boreal zone.

In this review, extreme events of temperature and precipitation is in focus as these have short and long-term implications for agricultural production.

2. Method

This synthesis focuses within the temperate- and sub-arctic climate zones. These zones corresponds to Swedish agro-climatic zones with similar climatic conditions (Beck et al. 2018; King et al. 2018; Ceglar et al. 2019). Effects of different extreme weather events are thus expected to have similar impact on cropping systems between nations within these zones.

Literature covering extreme temperature and precipitation events were achieved through a partially systematic approach in the search engine Web of Knowledge[2] during the period January 2020 to November 2020. Terms used in the search queries are shown per focus area in Table 1. The terms were combined using the links "AND" and "OR". The bulleted sections were separated by parentheses. The search was supplemented with secondary references achieved from reviewed publications in the primarily search. Additional grey literature was obtained by using the queries in Table 1 in webpages hosted by Swedish authorities.

Table 1. Search queries for Extreme weather definitions. The queries were 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*;

References were initially included based on title and if they had an initiation of including information on climate and extreme weather and agriculture. A second selection was done based on abstract content. A reference was included if it mentioned quantitative analysis of extreme weather and impact on agriculture, related to crop production.

From the references analyzed in full, following information was collected:

> 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.

Note that not all information was available for all reviewed studies.

[2] *www.webofknowledge.com*

3. Results

3.1. Geographic specifications and overview of reviewed publications

This review of extreme weather quantified thresholds of temperature and precipitation indices is based on n =33 references. A complete reference list is included in Appendix, Table 4. 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. Most literature is published after year 2000 except from two (n = 2) studies that were published 1972 and 1997 respectively (Figure 1).

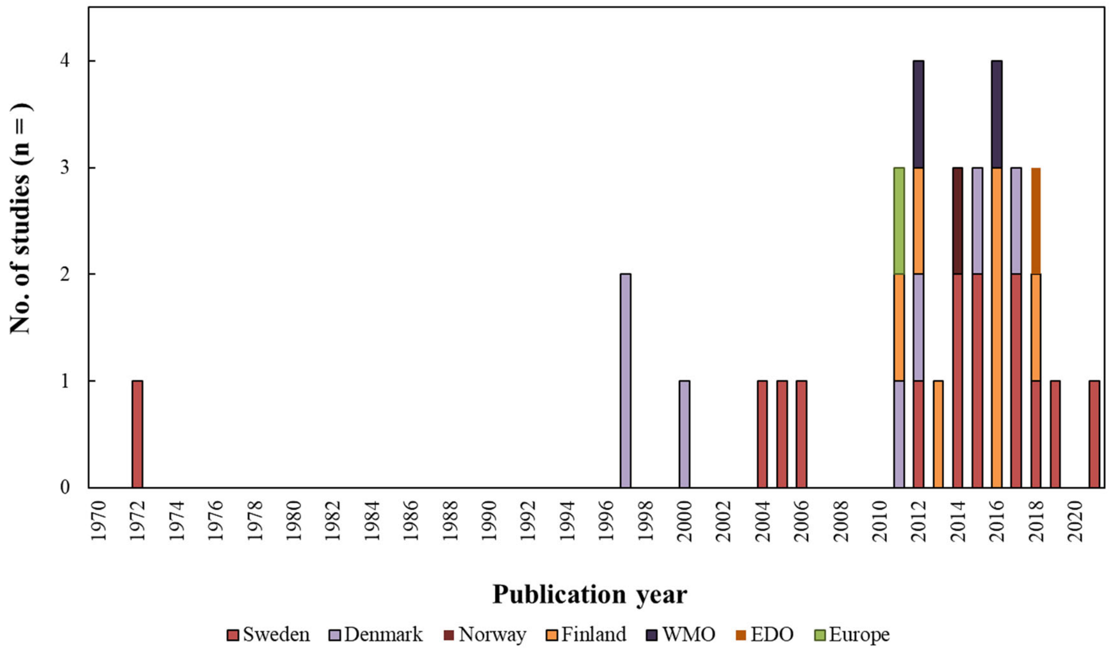


Figure 1. Number of reviewed publication per publication year divided per nation/source

The definitions used in the 33 references show an overall weight towards meteorological definitions related to precipitation. Temperature related definitions are more directly linked to potential impact on crop production and specifically yield levels. In total, 88 individual quantitative definitions were identified from the publications covering extreme precipitation (n = 22), drought (n = 13), heat (n = 14), cold (n = 25) and aridity index (n = 14) (Table 2).

Table 2. Number of classifications of extreme event indices/definitions from reviewed material identified 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)

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

3.2. Start- end and duration of crop season and sowing conditions

Extreme weather definitions from a crop production perspective, should reflect impacts on germination, 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, i.e., pre- and post-crop growth period. In temperate –boreal climatic zones, the start (onset) and end of cop seasons are typically defined by air and soil temperature, and at high latitudes also by day light conditions. This is unlike crop season onset and end typically defined in monsoonal tropical and sub-tropical agro climatic zones. Here, seasonal rainfall and soil moisture conditions typically define onset and length of crop seasons.

Minimum germination temperatures from literature are ranging from 1°C (cereals, peas) up to 8 °C (potatoes) (Geisler 1983; Gunnarson 2012; Johnsson 2016). However, the temperature thresholds used for determining the actual temperature for sowing and temperature sum during the crop season can be classified differently. For example Olesen et al. (2012b) used fixed base temperatures of 5 to 8°C for estimating temperature sum, while mean temperature was determined individually for wheat (7.1°C), oats (6.1°C) and maize (10.1°C) respectively. Sowing temperature was determined differently with higher temperature for wheat and oats at increasing latitude (Olesen et al. 2012b).

The crop season can be classified as the period when temperature and soil moisture sustain crop growth (Carter 1998). From a crop production perspective, seed bed preparation and sowing might not occur at start of the climatological growing season. Rather the agricultural production is dependent on the farmers' decisions and timings, as well as suitable soil conditions for seedbed preparation, in addition to a relevant temperature criterion. For example, dates for actual sowing in Sweden typically occurs as soon as the soil is thawed and dried (Håkansson et al. 2002), thereby being defined both by air and soil temperature, as well as soil moisture conditions. This review found a consensus for definition of the start of crop season by various references. The Expert Team on Climate Change Detection and Indices (ETCCDI) classified the start as daily average temperature ≥ 5°C for six continuous days (ETCCDI 2009; Zwiers & Zhang 2009). This 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 (a term not defined in the publication) or if a significant snow cover occurs (Johansson 1973).

A more elaborated definition for seasonal onset 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*

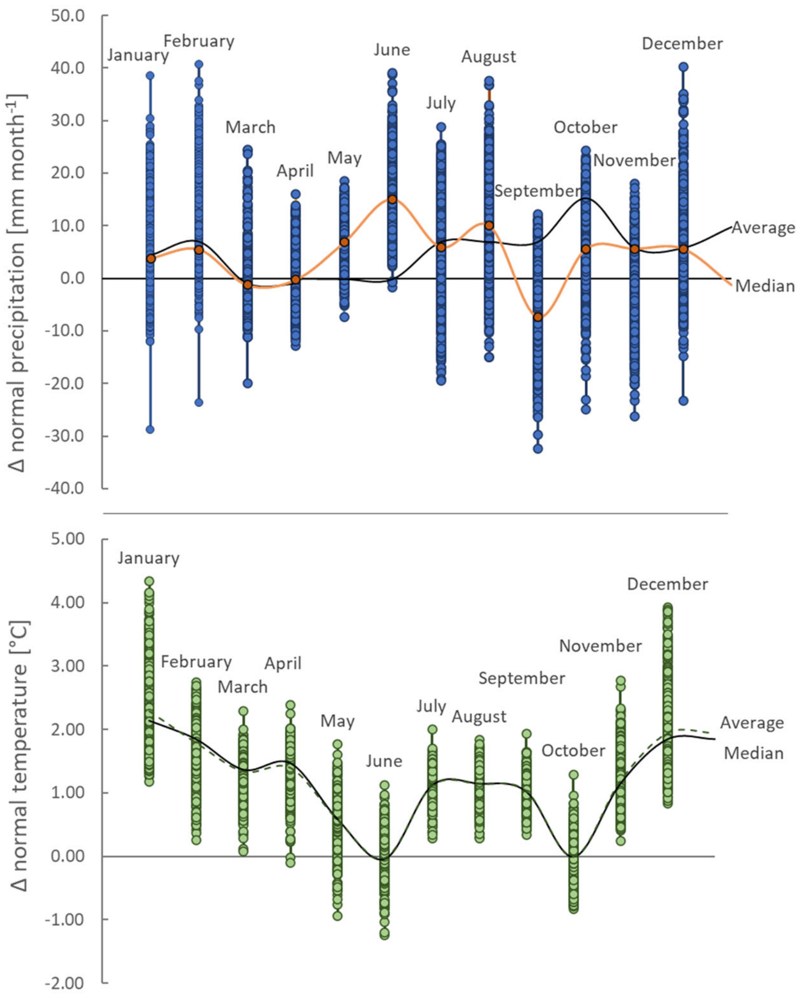


Figure 2 . Shift in monthly normal temperature and monthly normal precipitation between the previous (1961-1990) and the new (1991-2020) reference periods for statistical weather parameters. The Graphs show the calculated difference per month between the new (1991-2020) and the previous (1961-1990) normal period for weather stations provided by SMHI. The values are calculated by subtracting normal values from the period 1961-1990 from normal values from the period 1991-2020. Median and average lines are calculated from the estimated differences in the full dataset (1356 stations for precipitation and 712 stations for temperature). 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]

of day is 9 hours and above. Spring lasts at least 2 weeks" (Mattson et al. 2018; *p. 21*). Day length > 9 hours take place approximately from 2nd to last week of February (SMHI 2020a). Average temperatures > 3 °C in Sweden has in 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 for referring to deviations in weather occurrences is set to 1991-2020 by the Swedish Meteorological Institute. The previous period was 1961-1990 (SMHI 2020c) (Figure 2). Thus, the criteria on day length might increase its relevance under climate change impact if climatic parameters will shift to be more influential on crop growth, while daylight will still be limiting for in crop development. 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).

Five degrees (5 °C) is an overall 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 often used as the base temperature when determining temperature sum during the cropping season (e.g. Himanen et al. 2013). Although this threshold varies depending on crop species, cultivar, and crop development stage due to different activation temperatures depending on which physiological process that is active. Examples of classification of the physiologically effective growing season based on spring cereals are 8.5-9.5 °C based on historical average sowing dates of spring cereals (reference year 1971-2000) (Peltonen-Sainio et al. 2009). Additional temperatures for physiologically effective growing season includes base temperatures for 0 °C or +5 °C for temperate crops (Peltonen-Sainio et al. 2009; Eckersten & Kornher 2012; Olesen et al. 2012b), and +6 °C (Eckersten et al. 2012; Eckersten & Kornher 2012; Nkurunziza et al. 2014), + 8 °C (Olesen et al. 2012b) 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) (Figure 3). Additionally, Trnka et al. (2011) included criteria on minimum temperatures suitable for crop growth to > 0 °C, no snow cover and evapotranspiration ratio $Et_a/ET_r > 0.4$ (see additional information in section *Dryspells and drought*).

Above thresholds indicate fixed temperatures for start of growing season. However, crops respond differently to temperature depending on their development stages and cultivar. Results by Salazar-Gutierrez et al. (2013) from three American locations and four different winter wheat cultivars show a range in base temperature and defined phenological development stages. Base temperatures ranged between 3.1°C to 8.1°C (planting to heading) and 10.6 °C to 18.4°C (heading to harvest), compared to 1.6°C to 8.4°C for the full growth period planting to harvest. See also TEXT BOX 1 for an additional Australian example.

TEXT BOX 1

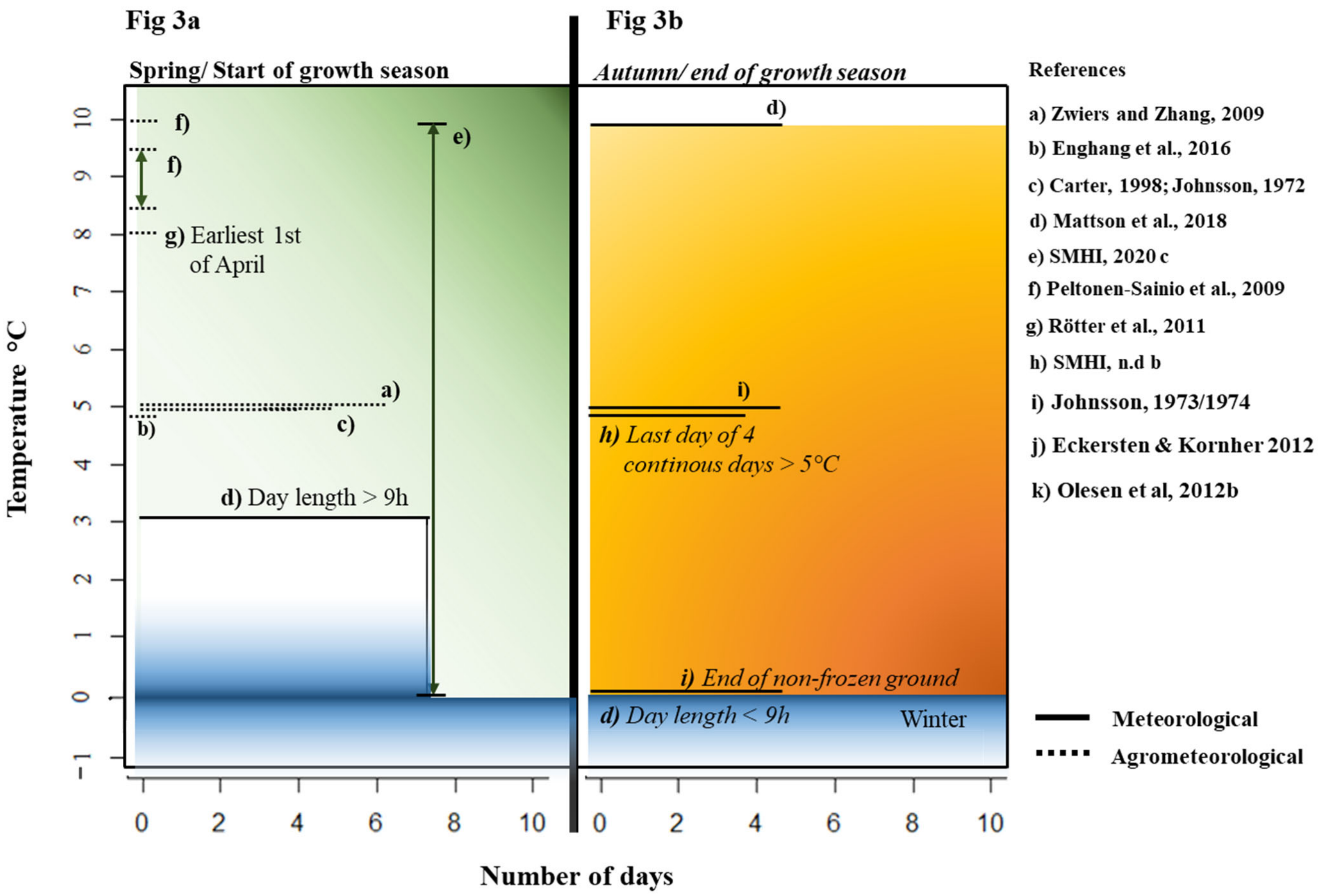
An Australian example of temperature response and base temperatures of wheat cultivar was presented by Slafer & Rawson (1995), which showed a relationship between phenological stage and base temperature, varying between -8.23 °C to 2.22 °C during growth to terminal spikelet initiation, 0.81°C to 1.83°C between terminal spikelet initiation to heading, and 7.28-8.96°C between heading to anthesis.

When using cultivar specific base temperatures, the cultivar variation in required thermal time from planting to harvest is reflected, by indicating the various cultivars individual thermal requirements for reaching maturity. The use of the common base temperature 0°C on the other hand indicate less variation between cultivars. Similarly, Bourgeois et al. (2000) studied effects of yield predictability of different pea cultivars by setting up models of growing degree days initiated by different base temperatures (in steps of 0.1°C between base temperature range from 0 - 10°C). Their results showed better predictability (lower coefficient of variation) with temperature threshold adapted to individual cultivar optimal threshold from 0 to 5 °C. As a cause of adaption to higher- or lower latitude and/or altitude, cultivars tolerance and growth response to cold temperatures varies. E.g. Olesen et al. (2012b), estimated the Huglin index[3] adjusted for growth latitude.

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 no.date b) and comparable by first occurrence after 1st July (1st Jan. in SH) of at least 6 consecutive days with < 5 ° per day (ETCCDI 2009; Zwiers & Zhang 2009). Comparably, autumn is defined as temperatures < 10°C during less than five consecutive days occurring after the 1st August (SMHI n.d:c). 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 $T_{average} \leq 5°C$ and that with the first five-day period have had a total average temperature ≤ 5°C. (Johansson 1973) (Figure 3).

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 period of non-frozen ground ends in autumn when daily

[3] Huglin index= temperature sum index for vine which uses 10 °C as base temperature



Spring	$T_{average}$ >3 °C and day length ≥ 9 h, lasting ≥ 2 weeks **(d) OR** Increasing $T_{average}$ > 0°C and < 10 °C for 7 continuous days (meteorological spring). **(e**
Start of growth season	Daily $T_{average}$ ≥ 5°C for 24 hours **(b) OR** Daily $T_{average}$ ≥ 5°C for 6 continuous days **(a)** **OR** $T_{average}$ > 5 °C for 4-5 continuous days during spring **(c)**
Physiologically effective growth season	$T_{average}$ during sowing 8.5-9.5 °C (based on historical average sowing dates 1971-2000) **(f) OR** $T_{average}$ ≥ 5 °C (temperate crops) **(f, j, k)** and ≥10°C (maize) **(f)** **OR** $T_{average}$ ≥ 8 °C and earliest 1st of April **(g)**
Autumn	$T_{average}$ ≤ 10 °C over 5 continuous days after 1st of August **(d)**
End of growth season	Last day of 4 consecutive days with $T_{average}$ > 5 °C **(h) OR** $T_{average}$ < 5 °C for five continuous days **(i)**
End of non frozen ground	$T_{average}$ < 0 °C for 5 consecutive days or when snow cover develops **(i)**
Winter	$T_{average}$ < 0 °C **AND** day length < 9 h **AND** starts earliest 2 weeks after start of autumn **(d)**.

*Figure 3. Visualization of definitions of start- and end of crop season, spring- and autumn. **(3a)** Show meteorological definitions of spring and growth season based on thresholds of minimum temperatures and duration above specified thresholds. Additionally, Figure 3a shows thresholds of base temperatures (minimum temperatures for crop growth) for specific crops relevant for Nordic conditions. **(3b)**. Figure 3b present maximum temperature and duration thresholds for definitions of autumn, winter and end of growing season. Despite two definitions of end of growth season, they are classified as meteorological due to the absence of including clear definition of either harvest or winter dormancy.*

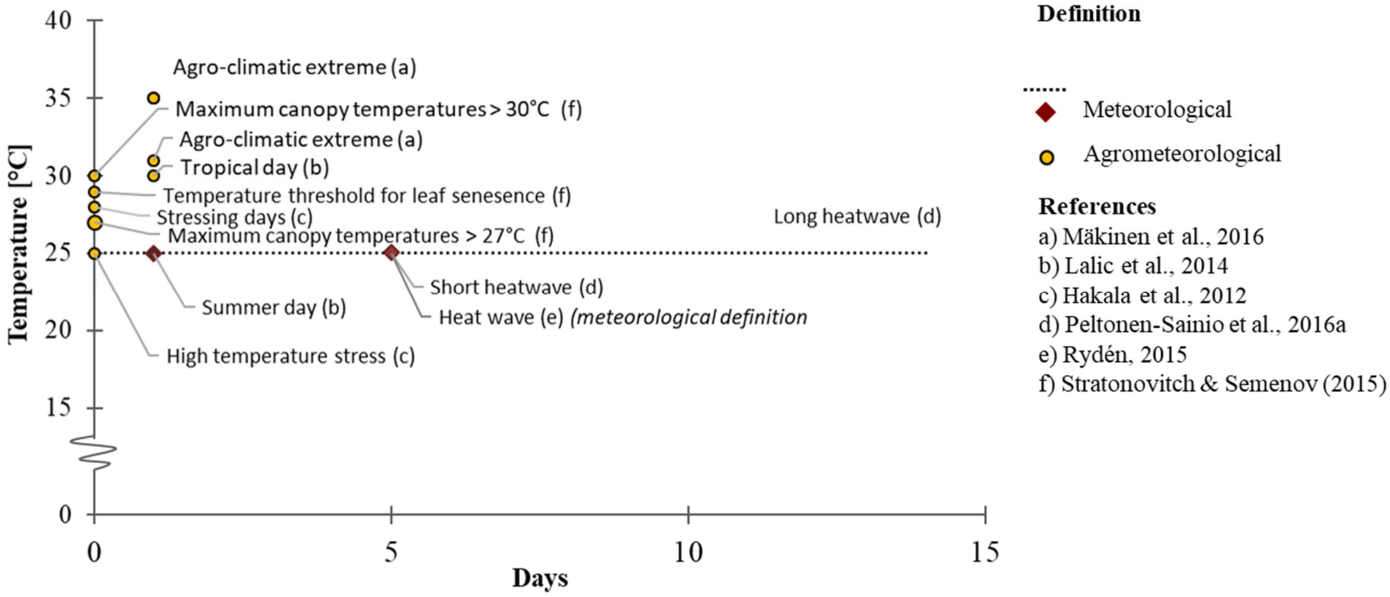
average temperatures reach < 0.0 °C for five consecutive days, or when a developed snow-cover occurs (Johnsson, 1973/1974). However, the period of vernalization for overwintering crops starts already at higher temperatures, e.g. 10°C for winter wheat (Fowler & Limin 2004; Fowler et al. 2014). Although, the temperature range for vernalization initiation can vary over a larger interval (15.7 to -1.3°C) (Porter & Gawith 1999; Fowler 2008). Threshold temperatures for initializing vernalization varies between crop species as well as between genotypes. For example, Fowler (2008) showed an upper vernalization threshold from 17.2 to 9.3 °C for different winter wheat varieties and a threshold of up to 19.6 °C for winter rye. Waalen et al., (2014) on the other hand set a fixed vernalization temperature of 5°C for winter rapeseed. The full vernalization period can be determined by a temperature sum accumulated from max- and min temperature thresholds of for vernalization to start and proceed, .(e.g Bergjord et al. 2008).

3.3. Extreme heat and heat waves

From a general perspective, definitions of heat waves and cold waves have been recommended to thresholds of max-, min- or mean temperatures under a period of at least three consecutive days based on an average climate period (Belusic et al., 2019). From a crop perspective, heat stress affect plants either direct- or indirect and the threshold temperatures for heat stress depends on plant development stage (e.g. Porter and Gawith, 1999; Wheeler et al., 2000). Heat that have negative effects on crops 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 5). These temperature thresholds indicate increased sensitivity for closing temperatures that have been defined for optimal photosynthesis. The latter occurs around 20-35 °C for C3-crops (Sage 2002; Porter & Semenov 2005; Sage & Kubien 2007, Machado & Paulsen 2001) and 30-40°C for C4-crops (Pittermann & Sage 2000; Sage 2002; Sage & Kubien 2007) due to light-saturation. Respiration on the other hand increases with temperature and net zero photosynthesis occurs at a threshold between 30 to 40°C (Pittermann & Sage 2000; Sage 2002; Porter & Semenov 2005; Sage & Kubien 2007).

Harmful temperatures for growth and development temperatures varies with crop species and development stage. Some examples of hazardous temperature limits are presented in Prasad et al (2017, Figure 1) who synthesized publications on optimum and damaging temperatures during reproductive stages. Harmful temperatures for crops relevant for Nordic conditions ranged between 30°C to 35 °C (cereals 30 °C (barley) to 35 °C (maize); oilseeds (mustard and rapeseed 35 °C); pulses (Faba bean 34°C to pea 35°C). Peas have previously reported to heat stress at 35°C (McDonald& Paulsen, 1997). Porter and Gawith (1999) presented lethal temperatures for wheat during sowing (32.7°C), vernalization (15.7°C), Terminal spikelets (>20°C), anthesis (31.0°C) and grain filling (35.4°C).

Optimal temperature for growth increase with the growth temperature that plants are adapted to. Yet, while assimilation efficiency by photosynthesis indicate relative stable performance for C3 over various growth temperatures, performance of assimilation efficiency for C4 plants increases with increasing growth temperature (Yamori et al. 2014). C3 crops has an advantage over C4 during low temperatures due to higher abundance of the enzyme Rubisco, as the enzyme reaches saturation of carbon dioxide faster at lower temperatures. Yet the enzyme activity increases with increased temperatures up to an optimum (Pittermann & Sage 2000). Estimated from energy transfer from solar radiation to energy incorporated in crop biomass, the energy-binding efficiency of incoming solar radiation is higher in C4 plants. Mainly due to reduced photorespiration favored by higher CO_2 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) Only three definitions were found concerning heat waves, that additionally include a temporal criterion. *Short heatwaves* were classified as temperatures ≥ 25 °C lasting over a period of at least 5 days, while *long heatwaves* were considered if the period of temperature ≥ 25 °C was extended over more than 14 days (Peltonen-Sainio et al. 2016).



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 **(a)**
Tropical day	Any day with Tmax > 30°C **(b)**
Summer day	Any day Tmax > 25 °C **(b)**
Stressing day	Number of days with Tmax ≥ 28°C 1 week before to 2 weeks after heading **(c)**
Short heatwave/Heatwave	Heat ≥ 25°C lasting 5 days **(d)**
Long heatwave	Heat lasting more than 14 days with less than 2 days with Tmax <25.1°C **(d)**
High temperature stress	≥ 25°C one week before heading to up till two weeks after heading **(c)**
Temperature threshold for leaf senesence	Temperature ≥ 28.93 °C **(f)**
Maximum canopy temperatures	≥ 27°C reduces number of fertile grains per unit of ear dry mass for heat sensitive wheat varieties **(f)** ≥ 30°C reduces potential grain weight for heat sensitive wheat varieties **(f)**

Figure 4. Magnitude and temporal scale for extreme high temperature events in Nordic countries related to crop production. The different definition8s are categorized as meteorological (red diamond, dotted line) or agrometeorological (full circles) based on if they consider specified impact related to crop growth and not solely weather parameters. Full references are displayed in Table 4 in Appendix.

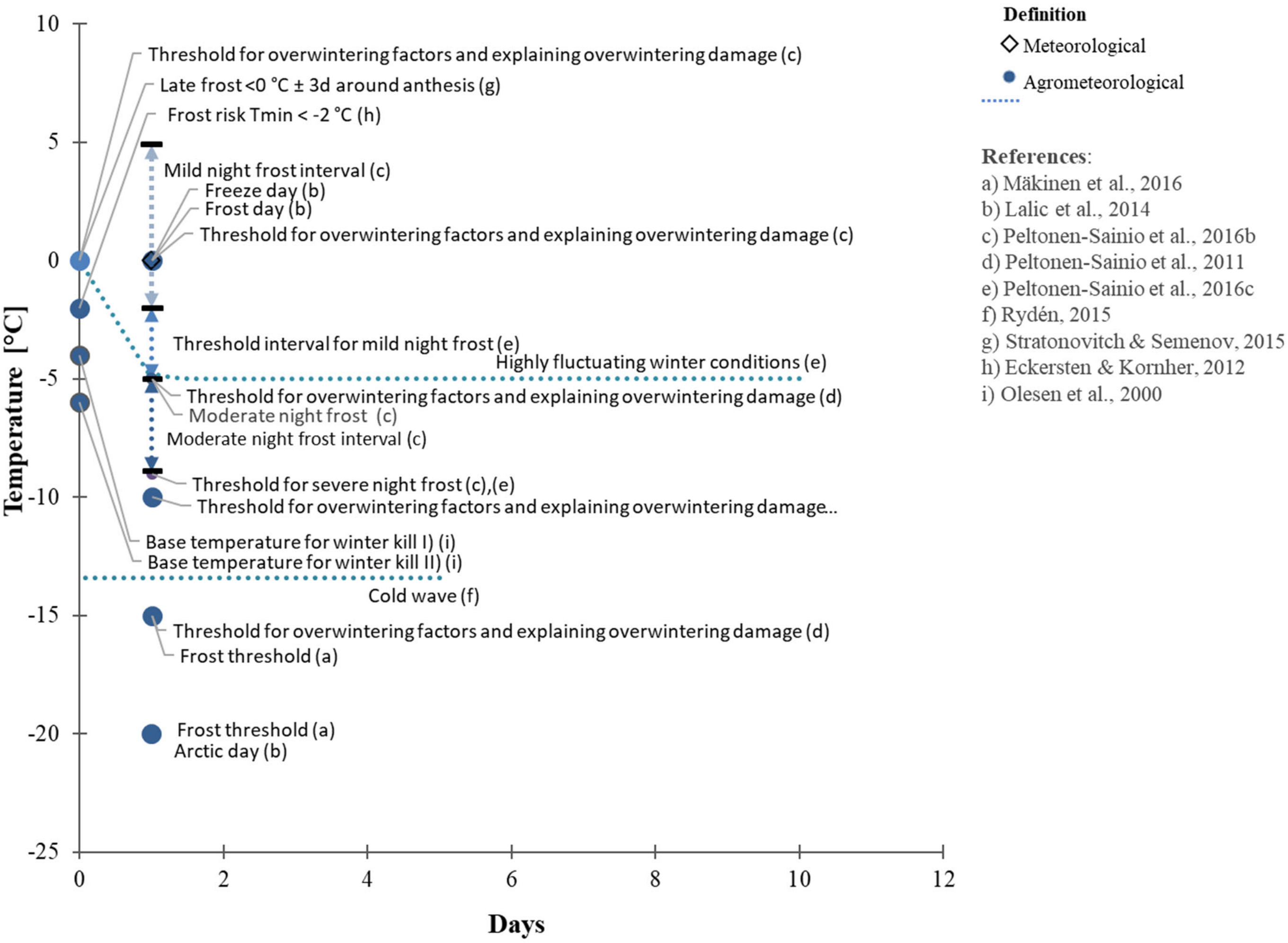
3.4. Frost, freezing and cold spells

Frost is meteorologically 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, ice 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 of -20 °C. Longer periods of cold waves have been defined as temperatures < -13.4°Cfor 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 by cold temperatures depend on magnitude, crop species, variety, vernalization period and winter dormancy (e.g. Porter & Gawith 1999; Waalen et al. 2014; Bergjord Olsen et al. 2018). Additional harmful effects due to cold periods can occur during spring when plant growth has been initiated and due to effects of presence/absence of an insulating snow cover. The snow cover reduces impact of cold temperature, but might lead to increased impact from biotic stresses (Vico et al. 2014).

3.5. Rainfall and precipitation

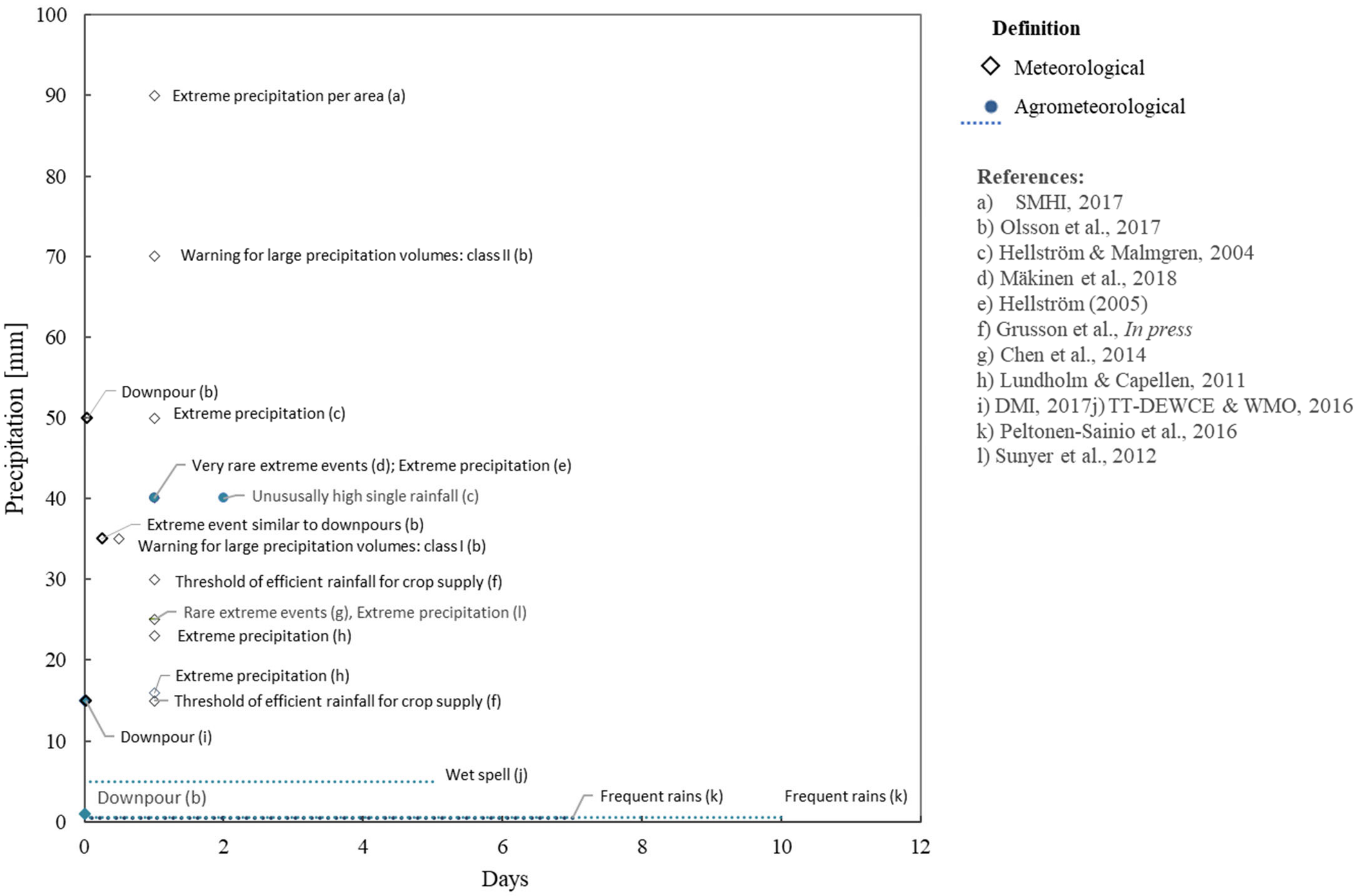
High precipitation is mainly defined by meteorological measures and is defined differently in magnitude depending on duration (Figure 6). The extreme variable of both low- and high rainfall is usually reliant on the reference period of average normal precipitation used in meteorology (standard precipitation of a 30yrs period – see *section 3.2* for Swedish normal periods). Despite aiming to use indices for interpretation of impact on agriculture. Thus, definitions of extreme precipitation do often not account for the agricultural or hydrological impact which are defined by lack of/excess soil moisture or high/low water flows or water levels. Duration of (high) precipitation events are important, both in meteorological as in agrometeorological classification. However, from an agricultural perspective, shorter periods within cropping seasons or over certain crop development stages are more important indication of potential hazardous impacts on crop yield, compared with longer time periods (monthly or annual) often used within meteorological classification. Although this differs from high-intensity events, characterized by high volume over a short time span (minutes or hours) which is equally important aspect to consider when designing/planning mitigation and adaptation measures.

Definitions of high- and/or extreme precipitation starts from *frequent rains* and *wet spells*, of which the former term is defined as a period of 7 days when rainfall exceeds 0.5 mm within 2 weeks and < 2 successive rainless days (< 0.5 mm). The accumulated precipitation for the 2 weeks should be higher than monthly mean precipitation (TT-DEWCE WMO, 2016). Similarly to above definition of frequent rain, *wet spells* are defined as >1mm precipitation per day over >5 consecutive days (TT-DEWCE WMO, 2016), i.e. a period of precipitation leading excess accumulation of higher water volumes. The same volumetric threshold yet without any threshold for duration of the event, is used by Breinl et al., (2020) and Zolina et al., (2013).(Figure 6). 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).



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



Extreme precipitation per area	> 90mm d^{-1} $1000m^{-2}$ (a)
Warning for large precipitation volumes:	Class II: > 70 mm 24 h^{-1} (b) Class I: > 35mm 12h^{-1} (b)
Downpour	≥ 50 mm h^{-1} (b) OR ≥ 1 mm min^{-1} (b) OR ≥ 15 mm 15 min^{-1} (i) OR ≥ 15 mm 30 min^{-1} (i)
Extreme precipitation	≥ 15 mm d^{-1} (h) OR ≥ 25 mm d^{-1} (h) OR ≥ 50 mm d^{-1} (c) OR ≥ 40 mm d^{-1} (e)
Very rare extreme event	≥ 40 mm d^{-1} (d)
Unusually high single rainfall	≥ 40 mm 48 h^{-1} (c)
Extreme event similar to downpours	≥ 40 mm 6 h^{-1} (b)
Threshold of efficient rainfall for crop supply	15 mm d^{-1} (f) OR > 30 mm d^{-1} (f)
Rare extreme events	≥ 25 mm d^{-1} (g)
Wet spell	Five consecutive days with precipitation > 1mm d^{-1} (j)
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 (k) 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. (k)

Figure 6. Magnitude and temporal scale for defining extreme precipitation events in Nordic countries related to crop production. The different definitions are categorized as meteorological (transparent diamond) or agrometeorological (blue circles,, dotted line) based on if they consider specified impact related to crop growth and not solely weather parameters Full references are displayed in Table 4 in Appendix

On the other end, *extreme precipitation* 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 under Swedish conditions (Olsson et al. 2017). *Excessive rainfall* directly related to agriculture has been defined as > 60 days with water saturation at field capacity of the soil (Mäkinen et al. 2018).. An example of extreme indices based on percentage of 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 in Sweden. They explicitly present years when deviations of precipitation sum during growth season (< 20mm over 40 days) and harvest season (> 100mm during August) respectively coincided with yield losses of 30 %, 50 % and 70% respectively. Yet comparisons of years with reduced yield linked to solely climatic indices gave inconsistent results, indicating that additional site-specific factors requires consideration when evaluating climatic impact on crop yield(Nkurunziza et al. 2015).

3.6. Soil saturation and flooding

Water is in a global perspecitve a main parameter that limits yields in rainfed systems. Yet excess water is an equal inhibitor of yields as water limitation (FAO 2020 p. 105). Crops requirer 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 water ponding in the unsaturated zone is a time limited agrological hazard due to high waterflow, snowmelt or high precipitation events. Too little water will limit these processes. Yet, too much water limits available oxygen for respiration processes to harmfully low levels. A critical lower limit for soil aeration for plants is defined to 0.05-0.10 m^3 air m^{-3} soil volume (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[4] (D). A threshold of 10 % air-filled porosity in a majority of soils occur under water content at a matric potential of 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 crop season. Too dry land reduces the possibility to achieve a good sowing bed. Excess soil water can affect soil structure negatively by crumbling or dispersion. This affects 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 cause 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[5] (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 is reduced with

[4] Degree of compactness is defined as "*…the dry bulk density of a soil layer in percent of a reference dry bulk density of the same soil obtained by a standardized, long-term uniaxial compression test at a stress of 200kPa ... similar to that of soil tillage*" (p. 72). The maximum value of D is 100 for the specified pressure of 200kPa induced to the soil (Håkansson & Lipiec 2000).

[5] The plastic limit is the lower soil water content when a soil is plastic, i.e., workable without resulting in cracking of the soil due to cohesion between soil particles in its semi-solid state (Keaton 2018).

lower soil organic carbon content and higher clay content (Dexter & Bird 2001; Obour et al. 2019a). Soils with higher clay content has a higher water content at wet- and dry tillage while the range of water content for when the soil is workable decreases (Obour et al., 2019b). The range of water content when the soil is workable (at soil matric tensions 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 threshold of 10 % clay has been estimated by Keller and Dexter, (2012) in order for soils to be plastic. Yet, considering other literature, the plastic limit might be lower due to impact of soil organic matter content.

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)

An example of applied limitations to harvest and sowing is used by Trnka et al.(2011). To determine suitable days of harvesting and sowing, the authors used a threshold of soil water content in top 0.1 m soil layer of > 10 % and < 70 %. water content Yet, they combined this threshold with an average daily temperature > 5 °C and daily precipitation ≤ 1mm during the same day followed by ≤ 5mm precipitation the preceding day (Trnka et al. 2011).

In addition to effects on yield and workability, soil water levels are important for microbial activity, as the water content affects the share of air-filled pores. 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 resulting in 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 we limited focus to direct impact on 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 has a return period < 10 years. *Medium* flood events were classified as return period between 10-100 years. *Large* flood events were classified as events with a return period >100 year (Burgess-Gamble et al. 2017). The main issue of heavy precipitation concerning agriculture occurs when precipitation volume exceeds infiltration capacity of soils. The result is either flooded areas where water naturally congregates at the point at rainfall, or surface runoff which potentially collects ad downstream locations.

Flooding is ,in contrast to soil saturation, a hazard from a landscape perspective with overflow of areas normally not situated under water (e.g. (UN n.d.). The flooding can occur due to high water levels from water bodies/water courses, due to high precipitation events, melting water or high groundwater level. 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 covered by a flooding event is important. It is a direct measure of impact severity on the surrounding area. Flooding per se is as already stated as a hydrological rather than agricultural index. However, soil saturation can be a cause for extended flooding, as well as can flooding on agricultural land due to e.g. deflecting surface water from nearby streams be a cause to soil saturation on agricultural land.

Important, but not directly linked to agrometeorological indices are the Swedish guidelines for evaluating flood risks that 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*) is defined by 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 of 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 value of production 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. As an example, this area was estimated to a reduction of 5000-12000 ha over the period 2010-2015 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 linked to an annual threshold can possibly be used as a benchmark for Swedish conditions and flooding severity. Flooding events that affect more than the threshold of land required for the annual growth of agricultural production to live up to the national food strategy can be seen as a precaution.

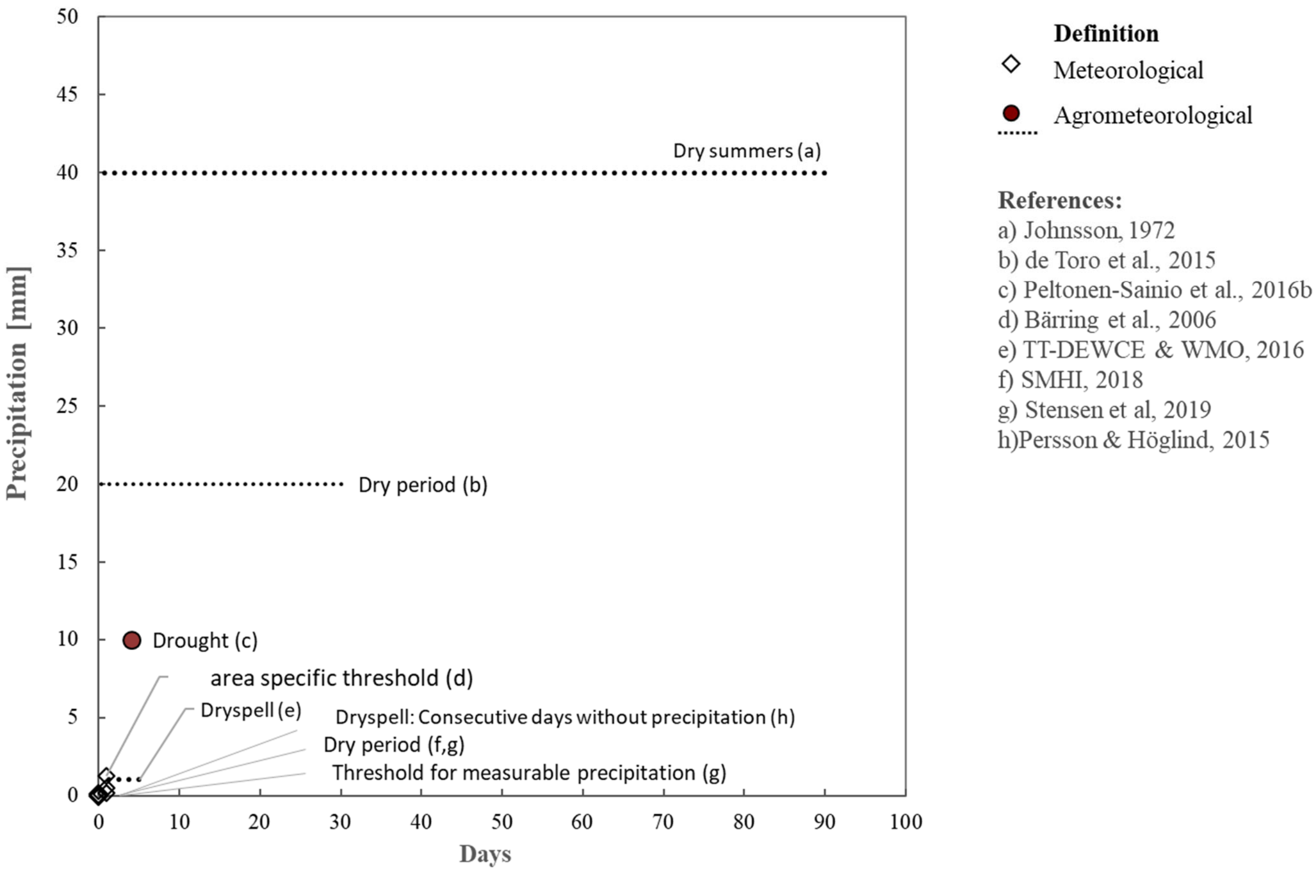
3.7. Dryspells and drought

Meteorological dry periods have been defined as precipitation < 0.1mm (Breinl et al. 2020) and < 0 mm d^{-1} (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 a dry period is often < 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). The latter is classed as the limit for measurable precipitation. As comparison, longer duration that can be classified as *dryspells* has been classified under the terms *dry summers* (< 40 mm between May and 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 7). The definitions of dryspells above are aimed for use concerning impacts of absence/reduction of precipitation on agriculture. However, absence of precipitation is not a direct reflection of severity for crop production. What is important is that definitions of drought from a meteorological perspective that just include precipitation deficit, does not imply the full effect on crop production (e.g. Barron et al. 2003).

Food and Agriculture Organization's terminology specify agricultural dryspells as

> "*Short period(s) of water stress during critical crop growth stages and which can occur with high frequency but with minor impacts compared with droughts*".
>
> (FAO 2010)

Agricultural dryspells affect crop production on one hand by lack of precipitation, and on the other hand through water available for plant uptake. Thus water partitioning of same volume of seasonal precipitation can enable higher- or lower yield based on site specific climatic conditions, soil- and water management as well as when dryspells occurs within the crop season (Rockström & Falkenmark 2000). The impact of dryspells on crop yield depends on crop species, the occurrence and magnitude of water deficit during the growth season and has more severe impact on yield during certain crop stages (Daryanto et al. 2017). Thus indices for dryspells need to reflect the variation in severity of short term water deficit of precipitation volumes, as well as available soil moisture volumes during individual growth seasons and crop development stages.



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

Figure 7. Magnitude and temporal scale for defining drought events in Nordic countries related to crop production. The different definitions are categorized as meteorological (transparent diamond) or agrometeorological (red circles,, dotted line) based on if they consider specified impact related to crop growth and not solely weather parameters Full references are displayed in Table 4 in Appendix

In relation to meteorological dryspell, additional site specific soil moisture and/or crop water demand and crop water use needs to be monitored or estimated to determine agricultural impact. Additionally, there is a possibility of precipitation during an agricultural dryspell, as the precipitation might not be sufficient to sufficiently fill soil water supply. Between these parameters there is a feedback response which is reflected in crop yield (reduction) due to stress factor/severity of the dryspells. The issue of monitoring agricultural dryspells which are varying in areal extent as well as temporarily during the growth season, there is a requirement in monitoring on high spatial and temporal scale. Using specified thresholds of dryspell-duration linked to prediction of occurrence of sensitive phenological crop stages by estimation of growing degree days (*see Section 3.2 and discussion on crop- and cultivar specific base temperatures*) (e.g. similar to method do determine phenological stages and effect on duration in forests under global warming, see Fu et al. (2015) might be a simple way to reduce requirement of otherwise high-frequent data for determining impact on crop yield by absence of precipitation and soil moisture.

Drought is defined differently with shorter or longer periods without water, depending on the weather patterns in different climate zones and if the considered area is naturally humid or dry (WMO 2010a). An important aspect of droughts is a requirement of a shorter or longer period of dry conditions (WMO 2010). Additionally, droughts can vary temporarily and over different area. Agricultural drought per definition is emanating from precipitation deficit, interlinked with meteorological circumstances but characterized by soil moisture deficit and not by the lack of precipitation (Das et al. 2003; 2010; IPCC 2021a). Thus, agricultural drought is linked to soil properties, -physical conditions and -biological factors (Wilhite & Glantz 1985; Destouni & Verrot 2014).

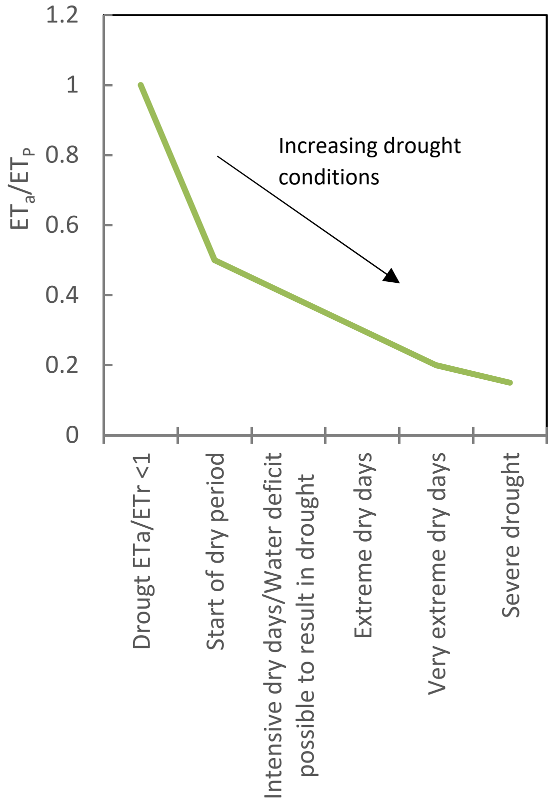


Figure 8. Thresholds for agrometeorological dry conditions defined by the ratio of actual evapotranspiration (ET_a) and potential evapotranspiration (ET_P).

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 8). Meteorological drought is defined differently with shorter or longer periods without water, depending on the weather patterns in different climate zones and if the considered area is naturally humid or dry (WMO 2010).

Two common 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. A change to positive SPI values indicate finalized drought. A SPI value ≥ 1.0 indicate conditions wetter than normal. 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). Only precipitation for determination of drought is considered within SPI. However, there is an important issue of 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). 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). They 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)

The term γ_t is the departure of climate for year *t*, $\bar{\gamma}$ 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 note that these definitions were still based on meteorological events and that synergetic effect from e.g. soil parameters, pests, nutrient cycling, and management strategies were not accounted for.

4. Discussion

Several definitions of extreme weather are used for Swedish agricultural purposes, both quantitative and qualitative (this study; Wiréhn 2021). To justify a full comparison between different thresholds for one defined extreme weather within crop- and climate modelling, the numbers must be interpreted based on the algorithm for which the number is inserted.

However , our study focusing on the temperate –boreal regions of NE Europe , note that often standards and thresholds use climatic indices, rather than relating to crop growth and –development For agro meteorological indices this study could not identify consistent standard based on precipitation and temperature . A specific gap was identified related to soil moisture and evapotranspiration associated with critical temperatures, high precipitation, and water ponding. Few definitions include duration of temperature thresholds, which is also an important aspect of crop damage, as both short shock events and events of longer duration unexpectedly high (low) can have negative impact, directly and indirectly, through impact on water availability, crop development and nutrient uptake. As different tolerance towards both high- and low temperatures varies between crop, cultivars and phenological stage, these magnitude thresholds naturally vary in literature when referring to temperature. One index that was not brought up to full extent during this review is the temperature sum. Temperature sum 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. 2012a; Peltonen-Sainio & Jauhiainen 2014). However, the theoretical sowing date is not a guarantee for earlier sowing in practice, 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 3.6). It has also been discussed that radiation and daylight may affect earlier crop season start, and potentially limit transfer of varieties suited to new temperature conditions may be limited due to radiation limits.

Extreme precipitation linked to agriculture has mainly been defined by meteorological definitions, with emphasis on dryspells and droughts, and thereby missing the impact on soil saturation. Further these indices are lacking consistency. Extreme precipitation, especially as hail, can have direct negative impact by causing mechanical damage on crops. This factor was not found in the reviewed literature. However it is relevant especially in plant breeding for increased resistant towards mechanical impacts. In addition, dryspells- and drought definitions has mainly been linked to meteorological definitions of periods without precipitation. However, agrometeorological drought seems to be more clearly defined compared to soil saturation. 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. (Mishra & Singh 2010; Destouni & Verrot 2014). 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 *3.2 Start- end and duration of crop season and sowing conditions*), it also put a requirement on the timeliness of fulfilling precipitation requirements. Sowing may be limited by precipitation conditions, 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.

There is a need for more harmonized agrometeorological definitions linked to heavy precipitation to account for soil saturation and flooding of arable land that links to preceding soil moisture levels and soil properties. Including soil moisture and especially soil saturation alongside extreme weather definitions is however more complex than the meteorological definition of heavy precipitation. This is due to that water ponding also depend on evapotranspiration, inherent soil conditions incl. Infiltration and drainage capacity. These parameters are consecutively dependent on temperature, soil, and crop properties.

This review shows that a synthesis is missing with basis in essential climate thresholds for crop production. We found that especially intra-annual thresholds for 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 standardize indices for agro meteorological aspects. However, to compare results between studies a more standardized approach to e definition of extreme should be agreed on.

Focusing on the agrometeorological perspective it is also essential to identify its hierarchical dependence on preceding meteorological or hydrological events. Severe effects in e.g., crop production does not necessarily require a meteorological or hydrological extreme to occur. Defining thresholds with negative implications for specific crops, depends on magnitude, distribution (frequency of occurrence) 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). Yet possibly exchange flooding to soil moisture saturation – as the created water mirror due to excess ponding water is not the main issue for crops. Rather it possibly contributes to a temporal increase in duration of soil saturation as larger water volumes can take longer to infiltrate or evaporate.

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 or even soil damage. However, a defined threshold level of “acceptable” crop damage (e.g. Edström and Karlsson, 2019) is needed to work 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).

5. Conclusions

Farmers and the agricultural sector will need better high temporal and spatial resolution understanding on weather conditions and risks for extreme weather as climate change advance. Extreme events related to weather and climate do not have standardized definitions, but is dependent on the sector, region and the context where the definition should be used. This review, focused on the temperate boreal regions of the Scandinavian Peninsula, show high degree of inconsistency for assessing agro-climatic indices related to temperature and precipitation for crop production. There is a need to develop agreed standard approaches from an agrometeorological lens. This can be combined with meteorological definitions to account for crop yield impacts, as well as give statistical measures on severity and temporal probabilities of occurrence. One example is by e.g. combining agricultural thresholds for durations and frequencies with statistical return periods of meteorological- and hydrological events. A shift to more standardized and expanded use of agrometeorological indices need to be supported by intra-seasonal data collection to identify impact during both sensitive and critical crop stages. These should be used for design of decision support, so crop producers can make relevant management decisions during and post /pre-season. By better informed agro-meteorological risks and probabilities, one understand cost –benefit implications of those management practices in intra-seasonal impacts. Yet, most important start 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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6. References

Arvidsson, J. & Bölenius, E. (2006). Effects of soil water content during primary tillage – laser measurements of soil surface changes. *Soil and Tillage Research*, 90 (1), 222–229. https://doi.org/10.1016/j.still.2005.09.005

Barlow, K.M., Christy, B.P., O'Leary, G.J., Riffkin, P.A. & Nuttall, J.G. (2015). Simulating the impact of extreme heat and frost events on wheat crop production: A review. *Field Crops Research*, 171, 109–119. https://doi.org/10.1016/j.fcr.2014.11.010

Bärring, L., Holt, T., Linderson, M.-L., Radziejewski, M., Moriondo, M. & Palutikof, J. (2006). Defining dry/wet spells for point observations, observed area averages, and regional climate model gridboxes in Europe. *Climate Research*, 31, 35. https://doi.org/10.3354/cr031035

Barron, J., Rockström, J., Gichuki, F. & Hatibu, N. (2003). Dry spell analysis and maize yields for two semi-arid locations in east Africa. *Agricultural and Forest Meteorology*, 117 (1), 23–37. https://doi.org/10.1016/S0168-1923(03)00037-6

Beck, H.E., Zimmermann, N.E., McVicar, T.R., Vergopolan, N., Berg, A. & Wood, E.F. (2018). Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Scientific Data*, 5 (1), 180214. https://doi.org/10.1038/sdata.2018.214

Bednar Friedl, B., Biesbroek, R., Schmidt, D.N., Alexander, P., Børsheim, K.Y., Carnicer, J., Georgpopoulou, E., Haasnoot, M., Le Cozannet, G., Lionello, P., Lipka, O., Möllmann, C., Muccione, V., Mustonen, T., Piepenburg, D. & Withmarsh, L. (In Press). 2022 Europe. In: Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., & Rama, B. (eds.) *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. https://report.ipcc.ch/ar6wg2/pdf/IPCC_AR6_WGII_FinalDraft_Chapter13.pdf [2022-03-14]

Belusic, D., Berg, P., Bozhinova, D., Bärring, L., Doescher, R., Eronn, A., Kjellström, E., Klehmet, K., Martins, H., Nilsson, C., Olsson, J., Photiadou, C., Segersson, D. & Strandberg, G. (2019). *Climate Extremes for Sweden*. SMHI. http://urn.kb.se/resolve?urn=urn:nbn:se:smhi:diva-5461 [2020-08-13]

Bergjord, A.K., Bonesmo, H. & Skjelvåg, A.O. (2008). Modelling the course of frost tolerance in winter wheat: I. Model development. *European Journal of Agronomy*, 28 (3), 321–330. https://doi.org/10.1016/j.eja.2007.10.002

Bergjord Olsen, A.K., Persson, T., Wit, A. de, Nkurunziza, L., Sindhøj, E. & Eckersten, H. (2018). Estimating winter survival of winter wheat by simulations of plant frost tolerance. *Journal of Agronomy and Crop Science*, 204 (1), 62–73. https://doi.org/10.1111/jac.12238

Bourgeois, G., Jenni, S., Laurence, H. & Tremblay, N. (2000). Improving the Prediction of Processing Pea Maturity Based on the Growing-degree Day Approach. *HortScience*, 35 (4), 611–614. https://doi.org/10.21273/HORTSCI.35.4.611

Breinl, K., Baldassarre, G.D., Mazzoleni, M., Lun, D. & Vico, G. (2020). Extreme dry and wet spells face changes in their duration and timing. *Environmental Research Letters*, 15 (7), 074040. https://doi.org/10.1088/1748-9326/ab7d05

Burgess-Gamble, L., Ngai, R., Wilkinson, M., Nisbet, T., Pontee, N., Harvey, R., Kipling, K., Addy, S., Rose, S., Maslen, S., Jay, H., Nicholson, A., Page, T., Jonczyk, J. & Quinn, P. (2017). *Working with natural processes_ evidence directory*. (SC150005). Bristol: Environment Agency.

Carter, T.R. (1998). Changes in the thermal growing season in Nordic countries during the past century and prospects for the future. *Agricultural and Food Science*, 7 (2), 161–179. https://doi.org/10.23986/afsci.72857

Ceglar, A., Zampieri, M., Toreti, A. & Dentener, F. (2019). Observed Northward Migration of Agro-Climate Zones in Europe Will Further Accelerate Under Climate Change. *Earth's Future*, 7 (9), 1088–1101. https://doi.org/10.1029/2019EF001178

Daryanto, S., Wang, L. & Jacinthe, P.-A. (2017). Global synthesis of drought effects on cereal, legume, tuber and root crops production: A review. *Agricultural Water Management*, 179, 18–33. https://doi.org/10.1016/j.agwat.2016.04.022

Das, H.P., CAgM Working Group on Agrometeorology Related to Extreme Events & World Meteorological Organization (eds.) (2003). *Agrometeorology related to extreme events*. Geneva, Switzerland: Secretariat of the World Meteorological Organization. (WMO; no. 943)

Destouni, G. & Verrot, L. (2014). Screening long-term variability and change of soil moisture in a changing climate. *Journal of Hydrology*, 516, 131–139. https://doi.org/10.1016/j.jhydrol.2014.01.059

Dexter, A.R. & Bird, N.R.A. (2001). Methods for predicting the optimum and the range of soil water contents for tillage based on the water retention curve. *Soil and Tillage Research*, 57 (4), 203–212. https://doi.org/10.1016/S0167-1987(00)00154-9

Eckersten, H., Herrmann, A., Kornher, A., Halling, M., Sindhoj, E. & Lewan, E. (2012). Predicting silage maize yield and quality in Sweden as influenced by climate change and variability. *Acta Agriculturae Scandinavica Section B – Soil and Plant Science*, 62, 151–165. https://doi.org/10.1080/09064710.2011.585176

Eckersten, H. & Kornher, A. (2012). *Klimatförändringars effekter på jordbrukets växtproduktion i Sverige – scenarier och beräkningssystem*. (Department of Crop Production Ecology. No. 14). Uppsala: Swedish University of Agricultural Sciences.

Edström, F. & Karlsson, J. (2019). *Vad är betydande negativ påverkan på jordbrukets markavvattningsanläggningar?* (2019:5). Jönköping: Swedish Board of Agriculture. https://www2.jordbruksverket.se/download/18.6e46bb716fc11d726428f54/1579522890723/ra19_5.pdf [2020-12-03]

Enghag, O., Hagerberg, A., Jakowlew, G., Sundin, S., Waldner, J. & Wallentin, J. (2016). *Jordbruket och väderrelaterade störningar - Konsekvenser av översvämningar för växtodling och djurhållning*. Jönköping: Jordbruksverket. https://www2.jordbruksverket.se/download/18.229ea55815233ba03904ce87/1452608879129/ovr373.pdf [2020-06-04]

Enghang, O., Hagerberg, A., Jakowlew, G., Sundin, S., Waldner, J. & Wallentin, J. (2016). *Jordbruket och väderrelaterade störningar - Konsekvenser av översvämningar för växtodling och djurhållning*. (OVR 373). Jönköping: Jordbruksverket. https://www2.jordbruksverket.se/download/18.229ea55815233ba03904ce87/1452608879129/ovr373.pdf [2020-10-26]

ETCCDI (2009). *Climate Change Indices - Definitions of the 7y core indices*. http://etccdi.pacificclimate.org/list_27_indices.shtml [2022-03-14]

ETCCDI (2020). *Climate Change Indices - Definitions*. http://etccdi.pacificclimate.org/indices_def.shtml [2022-03-14]

European Parliament and the Council (2007). *Directive 2007/60/EC on the assessment and management of flood risks*. (L288). European Parliament & the Council of the European Union. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32007L0060&qid=1611570606990&from=EN [2021-01-25]

FAO (2010). *Dry spell. Terminology(A16.1)(A7.10/CSCM)*. https://www.fao.org/faoterm/en/ [2022-02-09]

FAO (2020). *The State of Food and Agriculture 2020. Overcomin water challenges in agriculture*. Rome: FAO. https://doi.org/10.4060/cb1447en

Fleig, A.K., Tallaksen, L.M., Hisdal, H. & Hannah, D.M. (2011). Regional hydrological drought in north-western Europe: linking a new Regional Drought Area Index with weather types. *Hydrological Processes*, 25 (7), 1163–1179. https://doi.org/10.1002/hyp.7644

Fowler, D. (2008). Cold Acclimation Threshold Induction Temperatures in Cereals. *Crop Science - CROP SCI*, 48. https://doi.org/10.2135/cropsci2007.10.0581

Fowler, D., Byrns, B. & Greer, K. (2014). Overwinter Low-Temperature Responses of Cereals: Analyses and Simulation. *Crop Science*, 54, 2395. https://doi.org/10.2135/cropsci2014.03.0196

Fowler, D.B. & Limin, A.E. (2004). Interactions among Factors Regulating Phenological Development and Acclimation Rate Determine Low-temperature Tolerance in Wheat. *Annals of Botany*, 94 (5), 717–724. https://doi.org/10.1093/aob/mch196

Geisler, G. (1983). *Adapted from Geisler, G. (1983). Ertragsphysiologie von Kulturarten des gemäßigten Klimas*. Berlin & Hamburg: Paul Parey.

Gulev, S.K., Thome, P.W., Ahn, J., Dentener, F.J., Domingues, C.M., Gerland, S., Gong, D., Kaufman, D.S., Nnamchi, H.C., Quaas, J., Rivera, J.A., Sathyendranath, S., Smith, S.L., Trewin, B., von Schuckmann, K. & Vose, R.S. (In press). Chapter 2. In: Masson-Delmotte, V., Zhai, A., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., & Zhou, B. (eds.) *The*

Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_02.pdf [2021-11-03]

Gunnarson, A. (2012). Såtid och sortvalets betydelse vid höstoljeväxtodling. https://www.svenskraps.se/2020/dokument/slutredovisning/07_satid_sortval_hostoljevaxter_albin-G_LINK.pdf [2020-03-17]

Hakala, K., Jauhiainen, L., Himanen, S.J., Rötter, R., Salo, T. & Kahiluoto, H. (2012). Sensitivity of barley varieties to weather in Finland. *The Journal of Agricultural Science*, 150 (2), 145–160. https://doi.org/10.1017/S0021859611000694

Håkansson, I., Arvidsson, J. & Rydberg, T. (2011). Effects of seedbed properties on crop emergence: 2. Effects of aggregate size, sowing depth and initial water content under dry weather conditions. *Acta Agriculturae Scandinavica, Section B - Plant Soil Science*, 61 (5), 469–479. https://doi.org/10.1080/09064710.2010.506447

Håkansson, I. & Lipiec, J. (2000). A review of the usefulness of relative bulk density values in studies of soil structure and compaction. *Soil and Tillage Research*, 53 (2), 71–85. https://doi.org/10.1016/S0167-1987(99)00095-1

Håkansson, I., Myrbeck, Å. & Etana, A. (2002). A review of research on seedbed preparation for small grains in Sweden. *Soil and Tillage Research*, 64 (1), 23–40. https://doi.org/10.1016/S0167-1987(01)00255-0

Harrington, L.J. & Otto, F.E.L. (2018). Adapting attribution science to the climate extremes of tomorrow. *Environmental Research Letters*, 13 (12), 123006. https://doi.org/10.1088/1748-9326/aaf4cc

Harvey, R.J., Chadwick, D.R., Sánchez-Rodríguez, A.R. & Jones, D.L. (2019). Agroecosystem resilience in response to extreme winter flooding. *Agriculture, Ecosystems & Environment*, 279, 1–13. https://doi.org/10.1016/j.agee.2019.04.001

Himanen, S.J., Hakala, K. & Kahiluoto, H. (2013). Crop responses to climate and socioeconomic change in northern regions. *Regional Environmental Change*, 13 (1), 17–32. https://doi.org/10.1007/s10113-012-0308-3

IPCC (2021a). Annex VII: Glossary. In: Matthews, J.B.R., Fuglestvedt, J.S., Masson-Delmotte, V., Möller, V., Méndez, C., van Diemen, R., Reisinger, A., & Semenov, S. (eds.) *Climate Change 2021: The Physical Science 37 Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press

IPCC (2021b). IPCC, 2021: Summary for Policymakers. In: Masson-Delmotte, V., Zhai, A., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., & Zhou, B. (eds.) *The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_02.pdf [2021-11-03]

Jia, G., Shevliakova, E., Artaxo, P., Noblet-Ducoudré, N.D., Houghton, R., House, J., Kitajima, K., Lennard, C., Popp, A., Sirin, A., Sukumar, R. & Verchot, L. (2019). SPM2 Land–climate interactions. In: Shukla, P.R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.C., Zhai, P., Slade, R., Connors, D., van Diemen, R., Ferrat, M., Haugney, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M., & Malley, J. (eds.) *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. 118

Johansson, W. (1973). *Metod för beräkning av vatteninnehåll och vattenomsåttning i odlad jord med ledning av meteorologiska data*. (Särtryck ur Grundförbättring 26 1973/74: 2-3). Avdelningen för Lantbrukets Hydroteknik Lantbrukshögskolan.

Johnsson, K. (2016). Temperaturens betydelse vid sådd. *Jordbruksaktuellt*. Jönköping. https://www.ja.se/artikel/50111/temperaturens-betydelse-vid-sdd.html [2020-08-13]

Johnsson, W. (1972). *Torr sommar, avdunstning och tillväxt*. (Mark-Växter 21: UDK 551.5;631.67). Uppsala: Lantbrukshögskolan.

Juhola, S., Klein, N., Käyhkö, J. & Schmid Neset, T.-S. (2017). Climate change transformations in Nordic agriculture? *Journal of Rural Studies*, 51, 28–36. https://doi.org/10.1016/j.jrurstud.2017.01.013

Keaton, J.R. (2018). Plastic Limit. In: Bobrowsky, P.T. & Marker, B. (eds.) *Encyclopedia of Engineering Geology. Encyclopedia of Earth Sciences Series*. Springer, Cham. https://doi.org/10.1007/978-3-319-73568-9

Keller, T., Arvidsson, J. & Dexter, A.R. (2007). Soil structures produced by tillage as affected by soil water content and the physical quality of soil. *Soil & Tillage Research*, 92 (1–2), 45–52. https://doi.org/10.1016/j.still.2006.01.001

Keller, T. & Dexter, A.R. (2012). Plastic limits of agricultural soils as functions of soil texture and organic matter content. *Soil Research*, 50 (1), 7. https://doi.org/10.1071/SR11174

King, M., Altdorff, D., Li, P., Galagedara, L., Holden, J. & Unc, A. (2018). Northward shift of the agricultural climate zone under 21 st -century global climate change. *Scientific Reports*, 8 (1), 7904. https://doi.org/10.1038/s41598-018-26321-8

Lalic, B., Eitzinger, J., Thaler, S., Vučetić, V., Nejedlik, P., Eckersten, H., Jacimovic, G. & Nikolic-Djoric, E. (2014). Can Agrometeorological Indices of Adverse Weather Conditions Help to Improve Yield Prediction by Crop Models? *Atmosphere*, 5, 1020–1041. https://doi.org/10.3390/atmos5041020

Lee, J.-Y., Marotzke, J., Bala, G., Cao, L., Corti, S., Dunne, J.P., Engelbrecht, F., Fischer, E., Fyfe, J.C., Jones, C., Maycock, A., Mutemi, J., Ndiaye, S., Panickal, S. & Zhou, T. (In press). Chapter 4. In: Masson-Delmotte, V., Zhai, A., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., & Zhou, B. (eds.) *The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_02.pdf [2021-11-03]

Lenton, T.M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W. & Schellnhuber, H.J. (2019). Climate tipping points — too risky to bet against. *Nature*, 575 (7784), 592–595. https://doi.org/10.1038/d41586-019-03595-0

Li, Y., Guan, K., Schnitkey, G.D., DeLucia, E. & Peng, B. (2019). Excessive rainfall leads to maize yield loss of a comparable magnitude to extreme drought in the United States. 13

Lipiec, J. & Hatano, R. (2003). Quantification of compaction effects on soil physical properties and crop growth. *Geoderma*, 116 (1), 107–136. https://doi.org/10.1016/S0016-7061(03)00097-1

Mäkinen, H., Kaseva, J., Trnka, M., Balek, J., Kersebaum, K.C., Nendel, C., Gobin, A., Olesen, J.E., Bindi, M., Ferrise, R., Moriondo, M., Rodríguez, A., Ruiz-Ramos, M., Takáč, J., Bezák, P., Ventrella, D., Ruget, F., Capellades, G. & Kahiluoto, H. (2018). Sensitivity of European wheat to extreme weather. *Field Crops Research*, 222, 209–217. https://doi.org/10.1016/j.fcr.2017.11.008

Malik, A.I., Colmer, T.D., Lambers, H., Setter, T.L. & Schortemeyer, M. (2002). Short-term waterlogging has long-term effects on the growth and physiology of wheat. *New Phytologist*, 153 (2), 225–236. https://doi.org/10.1046/j.0028-646X.2001.00318.x

Mattson, E., Johansson, T., Wallentin, J., Jakowlew, G., Nyberg, M. & Noreen, A. (2018). *Avvattning av jordbruksmark i ett förändrat klimat*. (2018:19). Jönköping: Swedish Board of Agriculture. https://www2.jordbruksverket.se/download/18.5bd82a281633701bda755c49/1525767877499/ra18_19.pdf [2020-06-02]

McPhillips, L.E., Chang, H., Chester, M.V., Depietri, Y., Friedman, E., Grimm, N.B., Kominoski, J.S., McPhearson, T., Méndez-Lázaro, P., Rosi, E.J. & Shiva, J.S. (2018). Defining Extreme Events: A Cross-Disciplinary Review. *Earth's Future*, 6 (3), 441–455. https://doi.org/10.1002/2017EF000686

Mishra, A.K. & Singh, V.P. (2010). A review of drought concepts. *Journal of Hydrology*, 391 (1), 202–216. https://doi.org/10.1016/j.jhydrol.2010.07.012

Mogensen, V.O., Jensen, C.R., Mortensen, G., Andersen, M.N., Schjoerring, J.K., Thage, J.H. & Koribidis, J. (1997). Pod photosynthesis and drought adaptation of field grown rape (Brassica napus L.). *European Journal of Agronomy*, 6 (3), 295–307. https://doi.org/10.1016/S1161-0301(96)02052-7

Mogensen, V.O., Jensen, C.R., Mortensen, G., Thage, J.H., Koribidis, J. & Ahmed, A. (1996). Spectral reflectance index as an indicator of drought of field grown oilseed rape (Brassica napus L.). *European Journal of Agronomy*, 5 (1), 125–135. https://doi.org/10.1016/S1161-0301(96)02016-3

Myndigheten för samhällsskydd och beredskap (2018). *Översyn av områden med betydande översvämningsrisk : enligt förordning (2009:956) om översvämningsrisker*. (MSB1152-Januari 2018). Karlstad: Myndigheten för samhällsskydd och beredskap - Enheten för brand- och olycksförebyggande arbete.

Nkurunziza, L., Kornher, A., Hetta, M., Halling, M., Weih, M. & Eckersten, H. (2014). Crop genotype-environment modelling to evaluate forage maize cultivars under climate variability. *Acta Agriculturae Scandinavica, Section B — Soil & Plant Science*, 64 (1), 56–70. https://doi.org/10.1080/09064710.2014.885076

Nkurunziza, L., de toro, A., von Rosen, D. & Henrik, E. (2015). Effects of extreme weather on yields of major cereal crops in Sweden: Analysis of long-term experiment data. *Aspects of Applied Biology*, 128 (Valuing long-term sites and experiments for agriculture and ecology)

Obour, P.B., Keller, T., Jensen, J.L., Edwards, G., Lamandé, M., Watts, C.W., Sørensen, C.G. & Munkholm, L.J. (2019a). Soil water contents for tillage: A comparison of approaches and consequences for the number of workable days. *Soil and Tillage Research*, 195, 104384. https://doi.org/10.1016/j.still.2019.104384

Obour, P.B., Keller, T., Lamandé, M. & Munkholm, L.J. (2019b). Pore structure characteristics and soil workability along a clay gradient. *Geoderma*, 337, 1186–1195. https://doi.org/10.1016/j.geoderma.2018.11.032

Obour, P.B., Kolberg, D., Lamandé, M., Børresen, T., Edwards, G., Sørensen, C.G. & Munkholm, L.J. (2018). Compaction and sowing date change soil physical properties and crop yield in a loamy temperate soil. *Soil and Tillage Research*, 184, 153–163. https://doi.org/10.1016/j.still.2018.07.014

Olesen, J.E., Børgesen, C.D., Elsgaard, L., Palosuo, T., Rötter, R.P., Skjelvåg, A.O., Peltonen-Sainio, P., Börjesson, T., Trnka, M., Ewert, F., Siebert, S., Brisson, N., Eitzinger, J., Asselt, E.D. van, Oberforster, M. & Fels-Klerx, H.J. van der (2012a). Changes in time of sowing, flowering and maturity of cereals in Europe under climate change. *Food Additives & Contaminants: Part A*, 29 (10), 1527–1542. https://doi.org/10.1080/19440049.2012.712060

Olesen, J.E., Børgesen, C.D., Elsgaard, L., Palosuo, T., Rötter, R.P., Skjelvåg, A.O., Peltonen-Sainio, P., Börjesson, T., Trnka, M., Ewert, F., Siebert, S., Brisson, N., Eitzinger, J., van Asselt, E.D., Oberforster, M. & van der Fels-Klerx, H.J. (2012b). Changes in time of sowing, flowering and maturity of cereals in Europe under climate change. *Food Additives & Contaminants: Part A*, 29 (10), 1527–1542. https://doi.org/10.1080/19440049.2012.712060

Olsson, J., Berg, P., Eronn, A., Simonsson, L., Södling, J., Wern, L. & Yang, W. (2017). *Extremregn i nuvarande och framtida klimat*. (Klimatologi, 47). Norrköping: SMHI.

van Oort, P.A.J., Timmermans, B.G.H. & van Swaaij, A.C.P.M. (2012). Why farmers' sowing dates hardly change when temperature rises. *European Journal of Agronomy*, 40, 102–111. https://doi.org/10.1016/j.eja.2012.02.005

Peltonen-Sainio, P. & Jauhiainen, L. (2014). Lessons from the past in weather variability: sowing to ripening dynamics and yield penalties for northern agriculture from 1970 to 2012. *Regional Environmental Change*, 14 (4), 1505–1516. https://doi.org/10.1007/s10113-014-0594-z

Peltonen-Sainio, P., Jauhiainen, L. & Hakala, K. (2009). Climate change and prolongation of growing season: changes in regional potential for field crop production in Finland. *Agricultural and Food Science*, 18 (3–4), 171–190. https://doi.org/10.2137/145960609790059479

Peltonen-Sainio, P., Venäläinen, A., Mäkelä, H., Pirinen, P., Laapas, M., Jauhiainen, L., Kaseva, J., Ojanen, H., Korhonen, P., Huusela-Veistola, E., Jalli, M., Hakala, K., Timo, K. & Virkajärvi, P. (2016). Harmfulness of weather events and the adaptive capacity of farmers at high latitudes of Europe. *Climate Research*, 67. https://doi.org/10.3354/cr01378

Pittermann, J. & Sage, R.F. (2000). Photosynthetic performance at low temperature of Bouteloua gracilis Lag., a high-altitude C4 grass from the Rocky Mountains, USA. *Plant, Cell & Environment*, 23 (8), 811–823. https://doi.org/10.1046/j.1365-3040.2000.00599.x

Porter, J.R. & Gawith, M. (1999). Temperatures and the growth and development of wheat: a review. *European Journal of Agronomy*, 10 (1), 23–36. https://doi.org/10.1016/S1161-0301(98)00047-1

Porter, J.R. & Semenov, M.A. (2005). Crop responses to climatic variation. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 360 (1463), 2021–2035. https://doi.org/10.1098/rstb.2005.1752

Pörtner, H.-O., Roberts, D.-C., Adam, H., Adelekan, I., Adler, C., Adrian, R., Aidunce, P., Ali, E., Ara Begum, R., Bedbar Friedl, B., Bezner Kerr, R., Biesbroek, R., Birkman, J., Bowen, K., Caretta, M.A., Carnicer, J., Casteallanos, E., Cheong, T.S., Chow, W., Cissé, G., Clayton, S., Constable, A., Cooley, S., Costello, M.J., Craig, M., Cramer, W., Dawson, R., Dodman, D., Efitre, J., Garschagen, M., Gilmore, E.A., Glavovic, B., Gutzler, D., Haasnoot, M., Harper, S., Hasegawa, T., Hayward, B., Hicke, J.A., Hirabayashi, Y., Huang, C., Kalaba, K., Kiessling, W., Kitoh, A., Lasco, R., Lawrence, J., Lemos, M.F., Lempert, R., Lennart, C., Ley, D., Lissner, T., Liu, Q., Liwenga, E., Liuch-Cota, S., Loschke, S., Lucatello, S., Luo, Y., Mackey, B., Mintenbeck, K., Mirzabaev, A., Möller, V., Moncassim Vale, M., Morecroft, M.D., Mortch, L., Mukherji, A., Mustonen, T., Mycoo, M., Nalau, J., New, M., Okem (South Africa), A., Ometto, J.P., O'Neill, B., Pandey, R., Permesan, C., Pelling, M., Pinho, P.F., Pinnegar, J., Poloczanska, E.S., Prakash, A., Preston, B., Racault, M.-F., Reckien, D., Revi, A., Rose, S.K., Schipper, E.L.F., Schmidt, D.N., Schoeman, D., Shaw, R., Simpson, N.P., Singh, C., Solecki, W., Stringer, L., Totin, E., Trisos, C.H., Trisurat, Y., van Aalst, M., Viner, D., Wairu, M., Warren, R., Wester, P., Wrathall, D. & Zaiton Ibrahim, Z. (In Press). Technical Summary. In: Pörtner, H.-O., Roberts, D.C., Poloczanska, E.S., Mintenbeck, K., Tignor, M., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., & Okem, A. (eds.) *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group IIto the Sxth Assessment Report of the International Panel on Climate Change*. Cambridge University Press. https://report.ipcc.ch/ar6wg2/pdf/IPCC_AR6_WGII_FinalDraft_TechnicalSummary.pdf [2022-03-13]

Rockström, J. & Falkenmark, M. (2000). Semiarid Crop Production from a Hydrological Perspective: Gap between Potential and Actual Yields. *Critical Reviews in Plant Sciences*, 19 (4), 319–346. https://doi.org/10.1080/07352680091139259

Rötter, R.P., Höhn, J., Trnka, M., Fronzek, S., Carter, T.R. & Kahiluoto, H. (2013). Modelling shifts in agroclimate and crop cultivar response under climate change. *Ecology and Evolution*, 3 (12), 4197–4214. https://doi.org/10.1002/ece3.782

Rötter, R.P., Palosuo, T., Pirttioja, N.K., Dubrovsky, M., Salo, T., Fronzek, S., Aikasalo, R., Trnka, M., Ristolainen, A. & Carter, T.R. (2011). What would happen to barley production in Finland if global warming exceeded 4°C? A model-based assessment. *European Journal of Agronomy*, 35 (4), 205–214. https://doi.org/10.1016/j.eja.2011.06.003

Rydén, J. (2015). A statistical analysis of trends for warm and cold spells in uppsala by means of counts. *Geografiska Annaler: Series A, Physical Geography*, 97 (3), 431–436. https://doi.org/10.1111/geoa.12083

Sage, R.F. (2002). Variation in the kcat of Rubisco in C3 and C4 plants and some implications for photosynthetic performance at high and low temperature. *Journal of Experimental Botany*, 53 (369), 609–620. https://doi.org/10.1093/jexbot/53.369.609

Sage, R.F. & Kubien, D.S. (2007). The temperature response of C3 and C4 photosynthesis. *Plant, Cell & Environment*, 30 (9), 1086–1106. https://doi.org/10.1111/j.1365-3040.2007.01682.x

Salazar-Gutierrez, M.R., Johnson, J., Chaves-Cordoba, B. & Hoogenboom, G. (2013). (Relationship of base temperature to development of winter wheat. 7 (4), 741–762

Salomon, E., Wesström, I. & Wivstad, M. (2019). Strategier i ekologisk produktion i Sverige för att öka resiliens mot extrem torka. *Future Food Reports 7*, 44

Seneviratne, Nicholls, N., Easterling, D., Goodess, G.M., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C. & Zhang, X. (2012). Changes in climate extremes and their impacts on the natural physical environment. In: Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.K., Allen, M., Tignor, M., & Midgley, P.M. (eds.) *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaption*. (A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC)). Cambridge, UK, and New York, NY, USA: Cambridge University Press, 109–230

Sharwood, R.E., Ghannoum, O. & Whitney, S.M. (2016). Prospects for improving CO2 fixation in C3-crops through understanding C4-Rubisco biogenesis and catalytic diversity. *Current Opinion in Plant Biology*, 31, 135–142. https://doi.org/10.1016/j.pbi.2016.04.002

Sivakumar, M.V.K., Motha, R.P., Wilhite, D.A. & Wood, D.A. (2010). *Agricultural Drought Indices. Proceedings of the WMO/UNISDR Expert Group Meeting on Agricultural Drought Indices, 2-4 June 2010, Murcia, Spain*. (AGM-11, WMO/TD No. 1572; WAOB-2011). Geneva, Switzerland: World Meteorological Organization.

SMHI (2017). *Extrem arealnederbörd | SMHI*. https://www.smhi.se/kunskapsbanken/klimat/extrem-arealnederbord-1.6153 [2020-02-19]

SMHI (2018). *Index som beskriver torka | SMHI*. https://www.smhi.se/kunskapsbanken/hydrologi/index-som-beskriver-torka-1.111164 [2020-02-18]

SMHI (2020a). *Dagslängdens förändring under året*. https://www.smhi.se/kunskapsbanken/meteorologi/dagslangdens-forandring-under-aret-1.7185 [2021-03-19]

SMHI (2020b). *Frost och markfrost*. https://www.smhi.se/kunskapsbanken/meteorologi/frost-och-markfrost-1.2789 [2021-01-28]

SMHI (2020c). *Ny normalperiod införs vid årsskiftet*. https://www.smhi.se/nyhetsarkiv/ny-normalperiod-infors-vid-arsskiftet-1.166724 [2021-01-14]

SMHI (2020d). *Vår*. https://www.smhi.se/kunskapsbanken/meteorologi/var-1.1080 [2020-10-19]

SMHI (n.d.a). *Årstidskarta*. https://www.smhi.se/vader/observationer/arstidskarta/ [2022-02-09]

SMHI (n.d). *Länsvisa klimatanalyser Klimatindexdefinitioner*. https://www.smhi.se/klimat/framtidens-klimat/lansanalyser/info/climate-index [2020-10-27]

SMHI (n.d.b). *Månads-årstids- och årskartor*. https://www.smhi.se/data/meteorologi/kartor/normal-manadsmedeltemperatur/alla-manader/med-temp [2021-03-19]

Snyder, Richard.L. & de Melo-Abreu, J.P. (2005). *Frost protection: fundamentals, practice, and economics - Volume 1*. (Volume 1). Rome: Food and Agriculture Organization of the United Nations. http://www.fao.org/3/y7223e/y7223e07.htm#bm07.2 [2020-07-01]

Stensen, K., Krunegård, A., Rasmusson, K., Matti, B. & Hjerdt, N. (2019). *Sveriges vattentillgång utifrån perspektivet vattenbrist och torka - Delrapport 1 i regeringsuppdrag om åtgärder för att motverka vattenbrist i ytvattentäkter*. (Hydrologi Nr 120). Norrköping: SMHI. https://www.smhi.se/polopoly_fs/1.152541!/Hydrologi_120.pdf [2020-07-01]

Sverige & Myndigheten för samhällsskydd och beredskap (2014). *Vägledning för översvämningskartering av vattendrag fakta, inspirerande exempel och tips för en bra beställning.* Karlstad: Myndigheten för samhällsskydd och beredskap (MSB). https://www.msb.se/sv/Produkter--tjanster/Publikationer/Publikationer-fran-MSB/Vagledning-for-oversvamningskartering-av-vattendrag/ [2021-01-25]

Svoboda, M.D., Fuchs, B.A., Integrated Drought Management Programme, World Meteorological Organization, Global Water Partnership, University of Nebraska--Lincoln, & National Drought Mitigation Center (2016). *Handbook of drought indicators and indices.*

de Toro, A., Eckersten, H., Nkurunziza, L. & von Rosen, D. (2015). *Effects of extreme weather on yield of major arable crops in Sweden*. (086). Uppsala. https://pub.epsilon.slu.se/12606/ [2020-07-01]

Trnka, M., Olesen, J.E., Kersebaum, K.C., Skjelvåg, A.O., Eitzinger, J., Seguin, B., Peltonen-Sainio, P., Rötter, R., Iglesias, A., Orlandini, S., Dubrovský, M., Hlavinka, P., Balek, J., Eckersten, H., Cloppet, E., Calanca, P., Gobin, A., Vučetić, V., Nejedlik, P., Kumar, S., Lalic, B., Mestre, A., Rossi, F., Kozyra, J., Alexandrov, V., Semerádová, D. & Žalud, Z. (2011). Agroclimatic conditions in Europe under climate change. *Global Change Biology*, 17 (7), 2298–2318. https://doi.org/10.1111/j.1365-2486.2011.02396.x

Trnka, M., Rötter, R.P., Ruiz-Ramos, M., Kersebaum, K.C., Olesen, J.E., Žalud, Z. & Semenov, M.A. (2014). Adverse weather conditions for European wheat production will become more frequent with climate change. *Nature Climate Change*, 4 (7), 637–643. https://doi.org/10.1038/nclimate2242

TT-DEWCE WMO (2016). *GUIDELINES ON THE DEFINTION AND MONITORING OF EXTREME WEATHER AND CLIMATE EVENTS*. WMO.

UN (n.d.). *UNTERM - The United Nations Terminology Database*. https://unterm.un.org/unterm/portal/welcome? [2021-03-19]

United Nations Framework Convention on Climate Change (2016). *Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 11 December 2015. Addendum. Part two: Action taken by the Conference of the Parties at its twenty-first session.* (FCCC/CP/2015/10/Add.1). Paris: United Nations.

Van Loon, A., Gleeson, T., Clark, J., van Dijk, A., Stahl, K., Hannaford, J., Di Baldassarre, G., Teuling, A., Tallaksen, L.M., Uijlenhoet, R., Hannah, D., Sheffield, J., Svoboda, M., Verbeiren, B., Wagener, T., Rangecroft, S., Wanders, N. & Van Lanen, H. (2016). Drought in the Anthropocene. *Nature Geoscience*, 9, 89–91. https://doi.org/10.1038/ngeo2646

Vicente-Serrano, S., Beguería, S. & López-Moreno, J.I. (2010). A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. *Journal of Climate*, 23, 1696–1718. https://doi.org/10.1175/2009JCLI2909.1

Vico, G., Hurry, V. & Weih, M. (2014). Snowed in for survival: Quantifying the risk of winter damage to overwintering field crops in northern temperate latitudes. *Agricultural and Forest Meteorology*, 197, 65–75. https://doi.org/10.1016/j.agrformet.2014.06.003

Waalen, W.M., Stavang, J.A., Olsen, J.E. & Rognli, O.A. (2014). The relationship between vernalization saturation and the maintenance of freezing tolerance in winter rapeseed. *Environmental and Experimental Botany*, 106, 164–173. https://doi.org/10.1016/j.envexpbot.2014.02.012

Wallentin, J., Sundin, S., Hagerberg, A., Andersson, M., Dahlberg, C., Enghag, O., Jakowlew, G., Waldner, J. & Widell, Lars.M. (2016). *Översvämning! Samhällets krisberedskap och förebyggande arbete när det* *gäller översvämningar som drabbar jordbrukssektorn*. (2016:01). Jönköping: Swedish Board of Agriculture. https://www2.jordbruksverket.se/download/18.4e4207e115c9b21270990a47/1497335547176/ra16_1.pdf [2020-06-02]

Wesström, I., Geranmayeh, P., Joel, A. & Ulén, B. (2016). *Översvämningar på jordbruksmark - utredning av konsekvenser på mark och produktion*. (16). Uppsala: Swedish University of Agricultural Sciences: Department of Soil and Environment - Hydrotechnics. https://pub.epsilon.slu.se/13612/7/wesstrom_i_etal_160915.pdf [2020-10-27]

Wheeler, T.R., Craufurd, P.Q., Ellis, R.H., Porter, J.R. & Vara Prasad, P.V. (2000). Temperature variability and the yield of annual crops. *Agriculture, Ecosystems & Environment*, 82 (1), 159–167. https://doi.org/10.1016/S0167-8809(00)00224-3

Wilhite, D.A. & Glantz, M.H. (1985). Understanding the Drought Phenomenon: The Role of Definitions. *WATER INTERNATIONAL*, 17

Wiréhn, L. (2021). Climate indices for the tailoring of climate information – A systematic literature review of Swedish forestry and agriculture. *Climate Risk Management*, 34, 100370. https://doi.org/10.1016/j.crm.2021.100370

WMO (2010). *Guide to Agricultural Meteorological Practices*. (WMO-No. 134). Genéve: World Meteorological Organization. https://www.wmo.int/pages/prog/wcp/agm/gamp/documents/WMO_No134_en.pdf [2020-06-30]

World Meteorological Organization (ed.) (1992). *International meteorological vocabulary/Vocabulaire météorologique international*. 2nd ed. Geneva, Switzerland: Secretariat of the World Meteorological Organization. (WMO/OMM/VMO; no. 182)

World Meteorological Organization (2021a). *New climate predictions increase likelihood of temporarily reaching 1.5 °C in next 5 years*. *World Meteorological Organization*. https://public.wmo.int/en/media/press-release/new-climate-predictions-increase-likelihood-of-temporarily-reaching-15-%C2%B0c-next-5 [2021-05-27]

World Meteorological Organization (2021b). *State of the Global Climate 2020*. (WMO-No. 1264). Geneveq, Switxerland. https://library.wmo.int/doc_num.php?explnum_id=10618 [2021-05-26]

Yamori, W., Hikosaka, K. & Way, D.A. (2014). Temperature response of photosynthesis in C3, C4, and CAM plants: temperature acclimation and temperature adaptation. *Photosynthesis Research*, 119 (1), 101–117. https://doi.org/10.1007/s11120-013-9874-6

Zhu, X.-G., Long, S.P. & Ort, D.R. (2008). What is the maximum efficiency with which photosynthesis can convert solar energy into biomass? *Current Opinion in Biotechnology*, 19 (2), 153–159. https://doi.org/10.1016/j.copbio.2008.02.004

Zolina, O., Simmer, C., Belyaev, K., Gulev, S.K. & Koltermann, P. (2013). Changes in the Duration of European Wet and Dry Spells during the Last 60 Years. *Journal of Climate*, 26 (6), 2022–2047. https://doi.org/10.1175/JCLI-D-11-00498.1

Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R.M., van den Hurk, B., AghaKouchak, A., Jézéquel, A., Mahecha, M.D., Maraun, D., Ramos, A.M., Ridder, N.N., Thiery, W. & Vignotto, E. (2020). A typology of compound weather and climate events. *Nature Reviews Earth & Environment*, 1 (7), 333–347. https://doi.org/10.1038/s43017-020-0060-z

Zwiers, F.W. & Zhang, X. (2009). *Guidelines on Analysis of extremes in a changing climate in support of informed decisions for adaptation*. (WCDMP-No. 72). Genéve: World Meteorological Organization. https://www.ecad.eu/documents/WCDMP_72_TD_1500_en_1.pdf [2020-04-15]

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 when Pday > 10 mm d-1	(Zwiers & Zhang 2009).
very heavy precipitation days	Number of days when 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 when 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
1	Bärring, L., Holt, T., Linderson, M-L., Radziejewski, M., Moriondo, M., Palutikof, J.P. (2006). Defining dry/wet spells for point observations, observed area averages, and regional climate model gridboxes in Europe.
2	Chen, D., Achberger, C., Ou, T., Postgård, U., Walther, A. & Liao, Y. (2014). Projecting Future Local Precipitation and Its Extremes for Sweden. Geografiska Annaler: Series of Physical Geography. Thematic Issue: Natural disaster science – A Nordic approach to integrated research on disaster risk. Vol. 97(1). pp. 25-39. Doi: https://doi.org/10.1111/geoa.12084
3	Copernicus European Drought Observatory (2018a). Heat and Cold Wave Indicator (HCWI. European Commission (EDO Indicator factsheet). Available https://edo.jrc.ec.europa.eu/documents/factsheets/factsheet_heatColdWaveIndex.pdf [2020-02-20]
4	de Toro, A., Eckersten H., Nkurunziza, L. & von Rosen, D. (2015). Effects of extreme weather on yield of major arable crops in Sweden. Uppsala: Swedish University of Agricultural Sciences. ISBN978- 91-576-9326-6
5	DMI, 2017. Hbad skal du forvente, når DMI varsler skybrud. Available: https://www.dmi.dk/da/nyheder/2017/hvad-skal-du-forvente-naar-dmi-varsler-skybrud/ [2020-01-30]
6	Eckersten, H. & Kornher, A. (2012). Klimatförändringars effekter på jordbrukets växtproduktion i Sverige - scenarier och beräkningssystem. Report from the Department of Crop Production Ecology (VPE) No.14. Swedish University of Agricultural Sciences (SLU). ISBN: 978-91-576-9067-8
7	Grousson, Y., Wesström, I., Svedberg, E. & Joel, A. (forthcoming). Influence of climate change on water partitioning in agricultural landscapes: Examples from Sweden. Dept. of Soil and Environment, Swedish University of Agricultural Sciences.
8	Hakala, K., Jauhiainen, L., Himanen, s.J., Rötter, R., Salo, T. & Kahiluoto, H. (2012). Sensitivity of barley varieties to weather in Finland. Journal of Agricultural Science. Vol. 150. pp. 145-160. Doi: https://doi.org/10.1017/S0021859611000694
9	Hellström, C. & Malmgren, B.A. (2004). Spatial Analysis of Extreme Precipitation in Sweden 1961-2000. Ambio. Vol. 33(4-5). pp. 187-192. Doi: 10.1639/0044-7447(2004)033[0187:SAOEPI]2.0.CO;2
10	Hellström, C. (2005). Atmospheric conditions during extreme and non-extreme precipitation events in Sweden. International Journal of Climatology. Vol. 25. Pp. 631-648. Doi: 10.1002/joc.1119
11	Johnsson, W. (1972). Torr sommar, avdunstning och tillväxt. Uppsala: Lantbrukshögskolan. (Mark-Växter 21: UDK 551.5; 631.67)
12	Lalic, B., Eitzinger, J., Thaler, S., Vučetić., Nejedlik, P., Eckersten, H., Jaimović & Nikolic-Djorić, E.B. (2014). Can Agrometeorological Indices of Adverse Weather Conditions Help to Improve Yield Prediction by Crop Models? Atmosphere. Vol. 5(4). pp.1020-1041. Doi: 10.3390/atmos5041020
13	Lundholm, S.C. & Cappelen, J. (2011). Extreme Value Analysis of 96 Daily Series of Precipitation, Denmark 1961-2010. DMI: Ministry of Climate and Energy. (Technical report 11-08). ISSN: 1399-1388
14	Mogensen, V.O., Jensen, C.R., Mortensen, G., Andersen, M.N., Schjoerring, J.K., Thage, J.H. & Koribidis, J. (1997). Pod photosynthesis and drought adaptation of field grown rape (Brassica napus L.). European Journal of Agronomy vol. 6(3-4). pp. 295-307. Doi: https://doi.org/10.1016/S1161-0301(96)02052-7
15	Mogensen, V.O., Jensen, C.R., Mortensen, G., Thage, J.H., Koribidis, J. & Ahmed, A. (1996). Spectral reflectamce index as an indicator of drought of field grouwn crops. European Journal of Agronomy. Vol. 5. pp. 125-135. Doi: https://doi.org/10.1016/S1161-0301(96)02016-3
16	Mäkinen, H., Kaseva, J., Trnka, M., Balek, J., Kersebaum, K.C., Nendel, C., Gobin, A., Olesen, J.E., Bindi, M., Ferrise, R., Moriondo, M., Rodríguez, A., Ruiz-Ramos, M., Takáč, J., Bezák, P., Ventrella, D., Ruget, F., Capellades, G. & Kahiluoto, H. (2018). Sensitivity of European Wheat to extreme weather. Field Crops Research. Vol. 222. pp. 209-217. Doi: https://doi.org/10.1016/j.fcr.2017.11.008
17	Olesen, J.E., Jensen, T. & Petersen, J. (2000) Sensitivity of field-scale winter wheat production in Denmark to climate variability and climate change. Climate Research. Vol 15. pp.221-238. Doi: 10.3354/cr015221
18	Olsson, J., Berg, P., Eronn, A., Simonsson, L., Söderling, J. & Yang, W. (2017). Extremregn i nuvarande och framtida klimat – Analyser av observationer och framtidsscenarier. SMHI (Klimatologi nr. 47). ISSN: 1654-2258
19	Peltonen-Sainio, P., Hakala, K. & Jauhiainen, L. (2011). Climate-induced overwintering challenges for wheat and rye in northern agriculture. Acta Agriculturae Scandinavica, Section B- Soil & Plant Science. Vol. 61(1). pp. 75-83. Doi: 10.1080/09064710903535977
20	a. Peltonen-Sainio, P., Pirinen, P., Mäkelä, H.M., Hyvärinen, O., Huusela-Veistola, E., Ojanen, H. & Venäläinen, A. (2016). Spatial and temporal variation in weather events critical for boreal agriculture: I Elevated temperatures. Agricultural and Food Science. Vol. 25. pp. 44-56. Doi: : 10.23986/afsci.51465
21	b. Peltonen-Sainio, P., Venäläinen, A., Mäkelä, H.M., Pirinen, P., Laapas, M., Jauhianien, L., Kaseva, J., Ojanen, H., Korhonen, P., Hussela-Veistola, E., Jalli, M., Hakala, K., Kaukoranta, T. & Virkajärvi, P. (2016). Harmfulness of weather events and the adaptive capacity of farmers at high latitudes of Europe. Climate Research. Vol. 67. pp. 221-240. Doi: 10.3354/cr01378
22	c. Peltonen-Sainio, P., Pirinen, P., Laapas, M., Mäkelä, H.M., Ojanen, H. & Venäläinen, A. (2016). Spatial and temporal variation in weather events critical for boreal agriculture: III Frost and winter time fluctuation. Agricultural and Food Science. Vol. 25. pp. 71-80. Doi: 10.23986/afsci.51467
23	Persson, T. & Höglind, M. (2014). Impact of climate change on harvest security and biomass yield of two timothy ley harvesting systems in Norway. Journal of Agricultural Science. Vol. 152. pp. 205-216. doi:10.1017/S0021859612001013

24	Rydén, J. (2015). A statistical analysis of trends for warm or cold spells in Uppsala by means of counts. Geografiska Annaler: Series A, Physical Geography. Vol. 97(3). pp. 431-436. Doi: 10.1111/geoa.12083
25	Rötter, R.P., Höhn, J., Trnka, M., Fronzek, S., Carter, T.R. & Kahiluoto. (2013). Modelling shifts in agroclimate and crop cultivar response under climate change. Ecology and Evolution. Vol.3 (12). pp. 4197-4214. Doi: 10.1002/ece3.782
26	Seneviratne, S.I., N. Nicholls, D. Easterling, C.M. Goodess, S. Kanae, J. Kossin, Y. Luo, J. Marengo, K. McInnes, M. Rahimi, M. Reichstein, A. Sorteberg, C. Vera, and X. Zhang, 2012: Changes in climate extremes and their impacts on the natural physical environment. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 109-230.
27	SMHI (2017). Extrem arealnederbörd. Available: https://www.smhi.se/kunskapsbanken/klimat/extrem-arealnederbord-1.6153 [2020-02-19]
28	SMHI (2018). Index som beskriver torka. Available: https://www.smhi.se/kunskapsbanken/hydrologi/index-som-beskriver-torka-1.111164 [2020-02-18]
29	Stensen, K.., Krunegård, A., Rasmusson, K., Matti, B. & Hjerdt, N.(2019). Sveriges vattentillgång utifrån perspektivet vattenbrist och torka – Delrapport 1 i regeringsuppdrag om åtgärder för att motverka vattenbrist i ytvattentäkter. SMHI. (Hydrologi Nr 120, 2019). ISSN: 0283-7722
30	Stratonovitch P, Semenov MA. Heat tolerance around flowering in wheat identified as a key trait for increased yield potential in Europe under climate change. Journal of Experimental Botany; v. 66(12), pp. 3599-3609. doi: 10.1093/jxb/erv070. Epub 2015 Mar 7. PMID: 25750425; PMCID: PMC4463804.
31	Sunyer, M.A., Madsen, H. & Ang P.H. (2012). A comparison of different regional climate models and statistical downscaling methods for extreme rainfall estimation under climate change. Atmospheric Research. Vol. 103. pp. 119-128. Doi: https://doi.org/10.1016/j.atmosres.2011.06.011
32	TT-DEWCE & WMO (2016). Guidelines on the Definition and Monitoring of Extreme Weather and Climate Events. Draft version – first reviewed by TT-DEWCE December 2015. TT-DEWCE, WMO: Draft. Available: https://www.wmo.int/pages/prog/wcp/ccl/opace/opace2/documents/DraftversionoftheGuidelinesontheDefinitionandMonitoringofExtremeWeatherandClimateEvents.pdf [2020-02-13]
33	Trnka, M., Olesen, J.E., Kersebaum, K.C., Skjelvåg, A.O., Eitzinger, J., Sguin, B., Peltonen-Sainio, P., Rötter, R., Iglesias, A., Orlandini, S., Dubrovský, M., Hlavinka, P., Balek, J., Eckersten, H., Cloppet, E., Calanca, P., Gobin, A., Vučetić, V., Nejedlik, P., Kumar, S.,Lalic, B., Mestre, A., Rossi, F., Kozyra, J., Alezandrov, V., Semerádová. D.& Žalud, Z. (2011). Agorclimatic conditions in Europe under climate change. Global Change Biology. vol. 17(7). 21pages. doi: 10.1111/j.1365-2486.2011.02396.x