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The vulnerability of European agricultural areas to anthesis heat stress increases with climate change

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Abstract.

Climate change poses a significant threat to agriculture, primarily through yield losses due to droughts and heatwaves. The flowering phase is a particularly critical period during which many crops are highly susceptible to heat, resulting in long-term damage and substantial yield reduction. By imposing the large-scale atmospheric circulation of the 2018 to 2022 heatwaves in a CMIP6 model, we explore the potential impact of such a multi-year event within future climate scenarios as a storyline. We developed a heat stress index to quantify the amount of stress experienced by crops due to heat exposure during flowering relative to unstressed conditions. This index was then applied to the storylines over the European domain and evaluated for major cereal crops (maize and wheat). Extrapolating 2022 conditions to a scenario with global warming of +4 K, we show that over 30% of the harvested area would experience severe heat stress, resulting in a 10% yield reduction across Europe. Our investigations highlight that the timing and severity of a heatwave can have a much higher impact than the mean warming level, emphasizing the need for accurate seasonal forecasts. Addressing these challenges will require proactive management adaptations, including dynamic forecast-based decisions on planting dates, crop, and variety selection.

1 Introduction

Climate change and food security are undeniably linked (Challinor et al. 2014). While it has been shown that a rise in mean temperatures may endanger the future of our current food system (Asseng et al. 2015; Zhao et al. 2017), the primary threat comes from the increasing intensity and frequency of extreme events such as droughts and heatwaves (Ciais et al. 2005; Vogel et al. 2019). As a result, crop yield losses are expected to show considerable temporal and spatial heterogeneity, with crop failure minimal in some years but widespread in others (Straussberger 2015). Significant heat-induced yield cuts have already been observed in Europe, especially during the frequent and widespread heatwaves from 2018 to 2022 (Beillouin et al. 2020; Baruth et al. 2022).

A rise in the frequency and intensity of extreme events is considered highly likely (Rahmstorf et al. 2011; Hoegh-Guldberg et al. 2018), continuing the trend of recent decades (Lesk et al. 2016; Perkins-Kirkpatrick et al. 2020). Future heatwaves will also come on top of a hotter baseline temperature, leading to an even higher impact on crop yields than observed in recent years (Heino et al. 2023). Furthermore, unless heatwave forecasting can be improved beyond the current limits of a few weeks in advance (Domeisen et al. 2023), crops will be sown with little idea of the likelihood of extreme events in the crucial late spring and summer periods. Consequently, agile, forecast-based mitigation strategies, such as yearly adaption of crop type, cultivar or planting date will be made difficult.

When assessing the impact of climate change on agriculture, the standard approach is to drive crop models using coupled climate models, such as those participating in the Coupled Model Intercomparison Project (CMIP) (e.g. Rosenzweig et al. 2014; Zhao et al. 2017; Müller et al. 2017; Zabel et al. 2021; Schmidt et al. 2024; Bathiany et al. 2023). However, it is well known that CMIP6 (and earlier iterations) under-represent the likelihood and severity of future heatwaves (Fan et al. 2020; Davini et al. 2020; Hirsch et al. 2021; Domeisen et al. 2023), e.g. the 2003 heatwave could not even be captured in re-forecasts (Weisheimer et al. 2011). Furthermore, assessments of future crop yields are typically averaged over multiple CMIP6 climate models, which themselves have differences in the spatial and temporal occurrence of heatwaves. As such, the effect of heatwaves is blurred out and absorbed into the uncertainty bounds of the crop yield predictions (Müller et al. 2021), leading to unrealistically low spatial and temporal variance.

Here we instead follow an event-based storyline approach, which has recently emerged as an alternative way of studying extreme events under climate change (Wehrli et al. 2020; van Garderen et al. 2021). A storyline is a physically consistent representation of a plausible future event such as a heatwave (Shepherd et al. 2018). By applying the dynamical forcing of a past event to future scenarios, the inherent intermodel spread due to dynamical changes is eliminated. Here, we reconstruct these extreme events in Europe by running a global-to-regional model chain. We first run a coupled climate model in which the global large-scale atmospheric circulation patterns are similar to those of the 2018 - 2022 period but in a +2, +3 or +4K warmer climate (Sánchez-Benítez et al. 2022). Then, we apply dynamical downscaling of the global storylines to produce high-resolution regional storylines of the same period (Klimiuk et al. 2024).

We focus on the effect of high temperatures in a period of a few days before and after flowering. During this critical period, crops are highly sensitive to heat stress, and excessive heat may result in long-term damage to the plant and substantial yield reduction in wheat (Porter et al. 1999; Prasad et al. 2014; Balla et al. 2019; Bheemanahalli et al. 2022) and in maize (Wahid et al. 2007; Rattalino Edreira et al. 2012; Cicchino et al. 2010). Temperatures around anthesis are what constitute our definition of a heatwave; a period of time, starting from one day, above a certain crop-specific threshold temperature. While the increased temperatures during the growing season may contribute to water stress, they are unlikely to cause plant heat stress (Cairns et al. 2013; Schmitt et al. 2022). Increased temperatures due to low soil moisture are considered in ICON-CLM, however, our model inherently does not include compounding effects of heat, as the crops are grown annually and heat levels experienced by crops therefore have no relation to heat experienced in the previous year. This would, of course, be different for perennial crops, which were not included in this study but is still an ongoing research topic (e.g. De Boeck et al. 2018; Zeng et al. 2021; Lesk et al. 2022), since previous heat stress can either have exacerbating or alleviating effects in case of a second stress event.

As part of assessing the impact of future heatwaves, we consider the effect of potential management adaptions aimed at mitigating the effect of heat stress. These include climate-driven changes to planting dates (Moriondo et al. 2011; Waha et al. 2012; Sacks et al. 2010; Iizumi et al. 2019) and crop cultivars that are better suited towards higher peak temperatures (Stone et al. 1994; Martre 2017; Bezner Kerr et al. 2022).

The purpose of this work is thus to make tangible the effect of plausible future heatwaves on European crop yields in warmer climates (+2, +3 and +4K), complementing traditional probabilistic scenario-based approaches that faithfully track changes in average temperatures, but often fail to capture heat extremes adequately. As part of this approach, we assess to what extent plausible management adaption strategies can mitigate the effect of future heatwaves.

2 Methods and Materials

We examine the effects of heat stress during the flowering periods on wheat (*Triticum aestivum L.*) and maize (*Zea mays*), Europe's most grown winter and spring-sown cereals (EuroStat 2024). Flowering times of most winter crops are quite similar, and winter wheat can therefore be seen as representative of crops such as winter barley or rye. Maize is highly vulnerable to yield loss due to extreme events and is therefore particularly interesting for such an analysis (Vogel et al. 2019).

2.1 Storyline Simulations

We used storylines from the AWI-CM1 climate model (Sánchez-Benítez et al. 2022). These simulations were branched off from CMIP scenario simulations at +2, +3 and +4K global-mean surface warming when the respective warming levels are reached. The simulations are then nudged towards ERA5 (Hersbach et al. 2020) reanalysis of large-scale wind data for the period 2017 - 2022, in which 2017 acts as a spinup year for the different model components. Thermodynamical variables and small-scale winds were allowed to develop freely (van Garderen et al. 2021; Sánchez-Benítez et al. 2022). Here we use five members of the AWI-CM1 simulations for CMIP6 (E1 - E5) which branched off from different ensemble members of the free-running climate model with different initial states for the atmosphere and ocean (Semmler et al. 2020; Sánchez-Benítez et al. 2022). The members are dynamically downscaled using the ICON (ICOsahedral Non-hydrostatic) model, Version 2.6.5.1 (Zängl et al. 2015) and configured for regional climate applications as ICON-CLM (ICON in Climate Limited-area Mode, see Pham et al. 2021) from a 1° global grid to a 0.11° grid over the Euro-CORDEX domain. In ICON-CLM, the Land-Feedback is integrated, and thus also spun up in the year 2017. To ensure that the present-day weather patterns are properly reproduced, we applied additional grid-point nudging of horizontal winds to the driving AWI-CM1 simulations at heights above 5000 m (Klimiuk et al. 2024). As shown in Klimiuk et al. 2024, dynamical downscaling improved the representation of near-surface temperature patterns in most of Europe and added essential regional details to global AWI-CM1stories. Thorough reality-checks and model performance evaluation for AWI-CM1 and ICON-CLM have been demonstrated in the respective papers (Sánchez-Benítez et al. 2022; Klimiuk et al. 2024). As this event-based nudging methodology is novel and has not yet been applied widely, we only apply the aforementioned model-chain (AWI-CM1 to ICON-CLM) to our data.

2.2 Plant growth and flowering

Grid-cell-specific flowering dates across Europe were determined using the concept of Growing Degree Days (GDDs). The GDD calculation follows that implemented in the plant development module $PlaMo^x$ of the process-based model Landscape DeNitrification-DeComposition (LandscapeDNDC) (Haas et al. 2013; Petersen et al. 2021). GDDs are accumulated throughout the growing season between sowing and maturity according to

$$aGDD = \sum GDD \tag{1}$$

$$GDD = (T_{avg} - T_{base}) * f_{chill} \tag{2}$$

where aGDD is the accumulated GDDs, T_{avg} the average daily temperature, T_{base} the species-specific baseline temperature and f_{chill} the vernalisation factor. This concept is widespread and used by many crop-system models (e.g. Jones et al. 2003; Nendel 2012; Moriondo et al. 2011, etc.).

Sowing for winter cultivars was started in 2017, since soil and atmosphere were spun up sufficiently by the time of sowing in october, while spring sown cultivars were introduced for 2018. For the baseline scenario planting and maturity dates were taken from the global crop calendar produced by Jägermeyr et al. 2021. This was constructed by combining national datasets spanning recent decades. We determined the associated flowering dates by first determining the grid-cell dependent aGDD at maturity, and then applying a species-specific fraction at which flowering occurs (54% for wheat, 55% for maize). For winter crops f_{chill} was calculated following the vernalisation routines described below, for spring and summer crops it is set to 1.

2.2.1 Vernalisation Requirements of winter wheat

Vernalisation is one of the main determinants of flowering date (Hyles et al. 2020) in winter crops. For winter crops plant development is delayed by a retardation factor f_{chill} if temperatures are insufficiently low for crop vernalisation. This is dependent on the accumulation of chill units (aCU) in the period before flowering according to

$$f_{chill} = \frac{aCU}{req\_CU} * chill\_influence \tag{3}$$

where

$$chill\_influence = \frac{aGDD - 0.5 \cdot GDD\_flowering}{0.5 \cdot GDD\_flowering} \tag{4}$$

with req_CU being the species-specific chill unit requirement for full vernalisation and $GDD\_flowering$ the species and grid-cell dependent accumulated growing degree days at which flowering occurs. $chill\_influence$ is a unit-less factor gradually increasing from 0 at half of the GDDs required for flowering to 1 at flowering.

The calculation of vernalisation requirements was also used to quantify the suitability of a region for growing winter wheat. If 70 % of the required chill units ($req\_CU = 35$ for winter wheat) were not met in a grid cell in at least one year, the grid cell was deemed unsuitable for growing winter wheat. The results were then compared with the suitability maps from the Global Gridded Crop Model Intercomparison Project (GGCMI) project.

2.3 Rule-based shifting of planting dates under future climate

Planting date adaption was based on changes to the mean climate in the +2, +3 and +4K storylines and to year-specific conditions in the planting period. The crop calendar by Jägermeyr et al. 2021 was used as a first guess, and planting dates adjusted using a rule-based algorithm summarised in Figure 1. The planting date was thus moved earlier if all conditions of no snow, no soil frost, and no heavy rainfall greater than 10 mm/d in the last 10 days were met. In case of heavy precipitation, it was additionally checked if the soil moisture exceeded the field capacity. If true, the planting date is delayed, since the soil was deemed unsuitable for heavy machinery. This approach is similar to the rules established by Sacks et al. 2010 and Iizumi et al. 2019, which also form the basis for the Jägermeyr et al. 2021 planting calendar. By adjusting the planting date stepwise day-by-day, we ensure that the risk of late spring frosts is not higher than in the planting calendar, since our method would stop advancing at the latest date when conditions would still be suitable for planting. To explore the mitigation potential of planting date adaption we compare the results of our calculations using the Jägermeyr et al. 2021 cropping calendar (henceforth referred to as static planting dates) with those arising from the adjusted planting dates (henceforth dynamic planting dates).

2.4 Heat Stress Index (HSI)

The impact of heat stress on crop yield was modelled via a Heat Stress Index (HSI) that is determined in the critical period starting 6 days before anthesis and continuing until 12 days after anthesis (Challinor et al. 2005; Moriondo et al. 2011; Nendel 2012). The HSI gives the fractional yield reduction due to heat stress and runs from 0 (full yield reduction due to heat stress) to 1 (no yield reduction due to heat stress). It is modelled as the minimum value of a heat stress factor (HSF),

$$HSI = \min(HSF_1, ...HSF_n) \tag{5}$$

where

$$HSF = 1 - \frac{T_{max} - T_{cr}}{T_{zero} - T_{cr}} \cdot F_f \qquad \text{if} \quad T_{max} > T_{cr} \tag{6}$$

The HSF is calculated for each separate period of heat stress within the anthesis period, defined as a set of consecutive days in which the maximum daily temperature (T_{max}) exceeds a critical temperature (T_{cr}). T_{cr} depends on both the timing of the

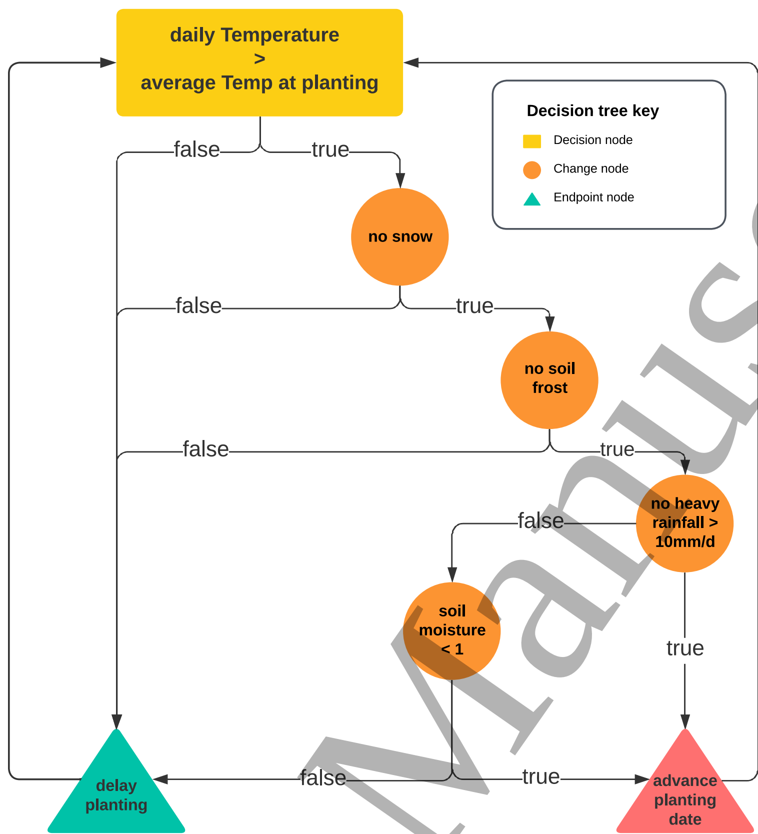

Figure 1: Rule-based decision tree for planting date adaptation. Planting is either advanced or postponed based on the climatological conditions of temperature, soil frost, snow cover, rainfall and soil moisture.

heat stress relative to anthesis (t) and on the duration of the heat stress (d) according to

$$-6 \leq t \leq 0 \begin{cases} T_{cr}(t) = \min[T_{cr}^{min}, 36 + S_c(t-6)] \\ T_{zero}(t) = 60 + S_l(t-6) \end{cases} \tag{7}$$

$$0 < t \leq 12 \begin{cases} T_{cr}(t,d) = \min[T_{cr}^{min}, 37.8 + 1.8t - 3d] \\ T_{zero}(t,d) = 52 + 0.75t - 1.5d \end{cases} \tag{8}$$

where T_{cr}^{min} is a species specific constant, $S_c = 0.3$ and $S_l = 2.5$. T_{zero} is the temperature of zero pod-set (i.e. maximum possible heat stress) and is also dependent on the timing of the heat stress relative to anthesis and the duration of the heat stress period. HSF also depends on the fraction of flowers (F_f) open during the high-temperature episode. For each event, the HSF is multiplied with the generalized flowering distribution following the approach used by Moriondo et al. 2011 in CropSyst, given by

$$F_f = \frac{1}{1 + (\frac{1}{0.015}) \cdot \exp(-1.4 \cdot daf)} \quad (9)$$

where daf is the number of days since flowering.

The lowest value of HSI per growing season is treated as the maximum impact. This model directly links heat stress to crop yield reduction, which was shown by Jin et al. 2016 to be the best way to model the impact of heat stress. The importance of including timing and duration-dependent parameters has been demonstrated by Barlow et al. 2015; Rezaei et al. 2015; Rötter et al. 2018. Similar anthesis heat stress models have been included in crop models such as GLAM (Challinor et al. 2005), CropSyst (Moriondo et al. 2011) MONICA (Nendel 2012), WOFOST (de Wit et al. 2021), SIMPLACE (Webber et al. 2016) and PEGASUS (Deryng et al. 2014) and used to study the impact of heat stress on a global scale (Osborne et al. 2013; Teixeira et al. 2013).

Model parametrisation was based on literature values determined via comparison to field measurements. Wheat has a relatively low threshold for heat stress of around 27°C close to anthesis, while for maize this lies between 32°C (Lobell et al. 2013) up to 37°C (Teixeira et al. 2013). Temperature thresholds for kernel abortion are around 35°C (Rezaei et al. 2015) and at temperatures above 38°C the pollen viability can also be affected, though Rattalino Edreira et al. 2012 found kernel sterility to be the primary cause of grain reduction. These findings are well reproduced using a T_{cr}^{min} of 25°C for wheat and 32°C for maize (Deryng et al. 2014)

HSI was determined on a yearly basis for each gridcell. Values were then grouped by increments of 0.1 from 0.5 to 1, as 0.5 was the largest observed reduction. The HSI was divided into five groups, labelled as *very severe* (0.5 - 0.6), *severe* (0.6 - 0.7), *medium* (0.7 - 0.8), *mild* (0.8 - 0.9), *weak* (0.9 - 1.0). A harvest index reduction would be equal to $1 - HSI$. To determine crop yield reductions on a European scale the HSI in each grid cell was combined with the crop-specific harvested area of each grid cell. This was determined by updating the MIRCA2000 dataset (Portmann et al. 2010) using country-specific harvested areas for 2018 - 2022 reported by FAOSTAT 2023.

2.5 Cultivar adaptation potential

Cultivar adaption is an obvious management strategy for decreasing the impact of heat stress during the flowering period, and can be achieved either through spatial shifting of cultivars or through breeding. While T_{cr} is adjusted by length and duration, making it dependent on the specific event, it is still constrained by T_{cr}^{min} for each crop. We vary the parameter T_{cr}^{min}, mimicking the heat stress resistance of different crop cultivars (Browne et al. 2021). For both wheat and maize we vary T_{cr}^{min} by ± 2K relative to the default value. By showing how different cultivars would react to elevated temperatures, we demonstrate the potential for exploring different cultivars either through shifting spatially or through breeding.

3 Results

3.1 Changes in crop growing suitability due to warming

The area suitable for growing winter wheat changes drastically throughout the different storyline scenarios (Figure 2). The warm summers coincided with mild winters, proving large areas of France to be unsuitable for winter wheat cultivation due to the winters not providing sufficient vernalisation, moving the share of winter wheat from 92 % of the wheat growing area estimated in Global Gridded Crop Model Intercomparison Project (GGCMI) to 83 % (Jägermeyr et al. 2021), and causing 24.1% of the traditional winter wheat area to be lost already in the present day climate. For +2K and +3K, this increases from 31 to 36% and up to 44% in the warmest scenarios of +4K background warming. Comparing data within the approach shows that a quarter of the suitable winter wheat growing area is lost between the present day and +4K climate. At the end of the century, the share of spring wheat would therefore increase from a current estimation of ca. 8% (GGCMI data) to up to 40 %.

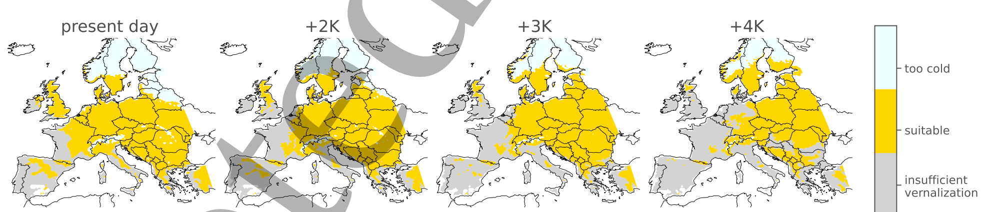

Figure 2: Shift in the suitability to grow winter wheat in the different storyline scenarios (present day, +2K, +3K, +4K). A pixel is deemed suitable for winter wheat if at least 70% of the chill units required for vernalisation were accumulated in at least one of the five winters.

3.2 Importance of heat stress during 2018 - 2022 (present day)

First, we analyse the impact of heat stress on wheat and maize during the heat episodes between 2018 and 2022 in the present climate. The temperatures during the growing seasons in those years were quite different from one another in the development of the heat in terms of timing and duration. Large extents of Europe experienced heat stress at least once during the reoccurring heatwaves throughout 2018 - 2022 for both maize and winter wheat.

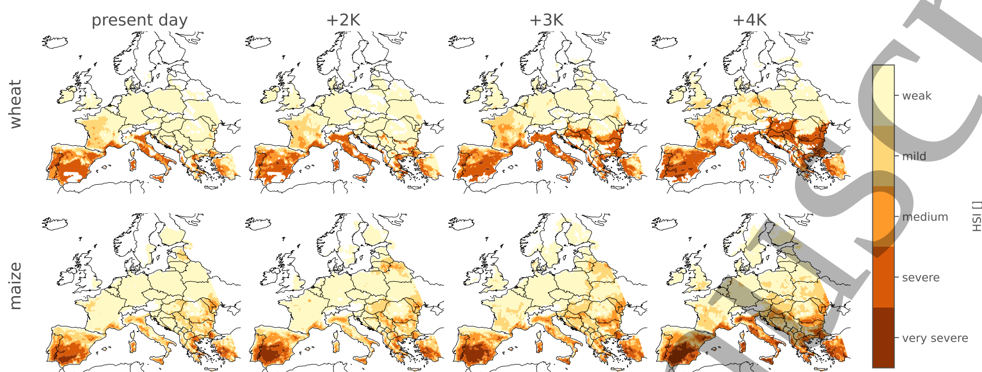

Figure 3: Average heat stress indices (HSI) for wheat (upper row) and maize (lower row) over the years 2018 - 2022 in the storyline scenarios (present day, +2K, +3K, +4K). Heat stress for wheat is determined by combining winter and spring wheat according to the suitability maps shown in Figure 2. *Very severe* heat stress corresponds to expected yield reductions between 40 - 50 %.

3.2.1 Wheat

The HSI for wheat is displayed as the combination of winter and spring wheat, combined according to suitability for growing winter wheat (see Section 3.1).

During present day conditions, the reduction in potential yields due to anthesis heat stress is on average 6.5% over the European domain (Figure 3). In 2018 we calculate 84% (24 Mha) of the harvested area for rain-fed wheat to have been affected by some form of heat stress, though the majority of the affected area (63 %,18 Mha) was only affected *weakly* (see Figure A1). Most of these *weakly* affected areas were located in the northeast of Europe. In 2019 and 2022 around 80 % of the harvested area was affected by at least *weak* heat stress, with 2.3 (670 kha) and 2.6 % (750 kha) affected by *severe* heat stress. The mean reduction of the harvest index over the entire domain was approximately 10% in 2019 and 2022. In 2019 parts of France also became more exposed to heat around anthesis, transitioning from only being *mildly* affected to *severely* affected, while in 2022 the main mechanism driving the reduction of the harvest index was an increase in *severely* affected areas predominantly in Spain. The majority of affected areas lie within regions considered spring wheat growing regions, such as Spain or Italy (see Figure A1). For spring wheat around 93 to 99 % of the area was affected by some form of heat stress, with the majority lying in the *severely* affected category, potentially reducing yield between 30 - 40 % due to anthesis heat stress. For winter-grown crops like winter wheat, the danger of heat stress is not as imminent, since the plants have the chance to develop in autumn, causing the flowering to occur earlier during milder weather. On average 27 % of winter wheat area experienced heat stress under the present day scenario, with 69 % only *weakly* affected, showing the current effect of heat stress on winter wheat is almost negligible. The results were similar if the whole of Europe was considered suitable for winter wheat (30 % *not* affected and 66 % *weakly* affected).

3.2.2 Maize

We estimate that during the 2018 - 2022 period between 68 - 98 % of maize harvested area was affected by some form of heat stress, with up to 6.7 % of maize harvested area experiencing severe heat stress in 2022 causing a yield loss due to heat stress of approximately 10% in the affected area (see Figure A3). From 2018 to 2019 an increase in affected areas is evident, but in 2020, 12% less area than in the previous year was affected by heat stress since 2020 was a non-extreme heat year compared to all other years (see Figure 5). The Mediterranean is one of the most affected areas. However, this changed depending on the timing of the heatwave, e.g. in 2021 most of the Iberian Peninsula was affected only *mildly*, whereas in 2018, 2020 and 2022 more than 50% of the Peninsula was affected by *very severe* heat stress levels, leading to a loss of between 40 - 50 % of maize yields in those areas (Figure A3). Most of central Europe showed no to mild affection levels of heat stress, especially in 2019 and 2021, despite record-breaking temperatures. It seems that the timing of the heatwave and the plant flowering did not align in a way of causing anthesis heat stress.

3.3 Heat stress in the storylines of the 2018 - 2022 period

By applying the storylines of the 2018 to 2022 period (Section 2.1), which included multiple heatwaves (Wehrli et al. 2020; Kueh et al. 2020; Lhotka et al. 2022), we can demonstrate how the impact of heatwaves could change under climate change. These storylines enable us to extrapolate present day results and make the impacts of climate change more tangible.

3.3.1 Wheat

The intensity of the heat stress for wheat increases across the climate change scenarios. From a 6.5% reduction of potential yields during the present day the HSI increases to an average 7.5, 9 and 11 % reduction on average over Europe in the considered scenarios (see Figure 3).

In the +2K scenario, the heat stress on wheat is not significantly different to present day conditions. Most changes are visible in the Iberian peninsula, where the areas affected would suffer from 40% up to 50% yield losses due to anthesis heat stress, although much of these areas do not primarily grow wheat. For wheat, 2018 is throughout all scenarios the year with the lowest HSI and also the highest harvest area affected (Figure 4), particularly in north-eastern Europe (Figure A1). The differences between the years is similar within the storyline simulations and the present day (Section 3.2.1). For the +3K and the +4K scenarios, there is a clear reduction of the HSI for the areas still cold enough for growing winter wheat (Figure 4), but also a significant reduction in areas meeting this criterion. Conversely, for spring wheat the trend is reversed. The modelled heat stress becomes much more relevant, with the affected area increasing from 4.3 ± 0.3 Mha to 12 ± 0.9 Mha and the *severely* affected areas increasing from 2.3 Mha to 6.4 Mha comparing present day and +4K.

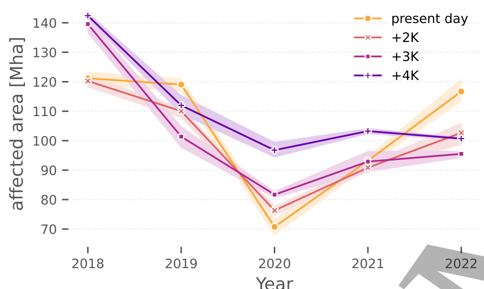

Figure 4: Sum of the wheat harvested area affected by anthesis heat stress over the European domain for the different storylines scenarios (present day, +2K, +3K and +4K). Every pixel where the Heat Stress Index (HSI) is less than 1 is considered affected, i.e., there is some yield reduction due to anthesis heat stress. Shading represents the full spread of the five ensemble members.

3.3.2 Maize

When examining the +2, +3 and +4K scenarios, a steady intensification of stress in areas already affected in the present day is evident (Figure 3). Flowering occurs on average 6 days earlier per storyline scenario due to higher temperatures during the growing season leading to a faster plant development (Figure 6). On average, the +4K scenarios show the largest affected area, but individual years in the +2K and +3K, and sometimes even in the present day scenario, show much larger affected areas due to the changes in flowering date relative to the heat episode (Figure 5). In comparing different years, 2021 and 2022 emerge as the most heat stress affected, with a yield loss of up to 15% across Europe in the +4K storyline. In 2021 large areas of eastern Europe, specifically south eastern Europe are affected by intense anthesis heat stress in the warming storylines. In terms of affected area, 2021 and 2022 show the highest shares throughout all future scenarios (10 - 11.8 Mha, see Figure 5) and the *severely* affected area increases from 6% in 2022 in the present day to over 15% considering the +4K scenario, with potential yield losses of up to 45% in Italy, Slovenia or Spain provided maize is grown there. Together with losses from less affected areas, Europe wide this could lead to a 10 % reduction of maize yields. Germany remains non-heat stressed in 2021 up until the +4K scenario (Figure A3). 2022 also shows high levels of stress throughout most of Europe, albeit the entire affected harvested area decreasing slightly in the +4K scenario as parts of northern Europe become less heat-stressed compared even to the present day.

As visible in Figure 5, while the present day, +2K and the +3K scenarios for 2022 all show an increase in the affected area from 2021 of an additional 1.6 Mha (1Mha; 0.7 Mha), in the +4K scenario affected area decreases by 0.3 Mha. This is mostly due to the 2021 heatwave initially being locally quite constrained to the western part of Europe, and Central Europe having quite low HSI levels, while 2022 showing are more homogeneous distribution in Europe (Figure A3). Throughout the warming levels, the 2021 heatwave spatially expands significantly, while the 2022 patterns show more of an intensification within already affected areas, leading to the overall affected area even decreasing as parts of northern Germany and Poland become unaffected.

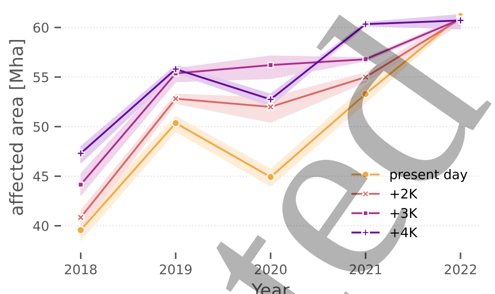

Figure 5: Same as figure 4 but for maize.

3.4 South-East Europe

The mean HSI over the heatwave period (Figure 3) generally shows a stronger impact in the south of Europe, but the yearly indices (Figure A3) show that the warming can

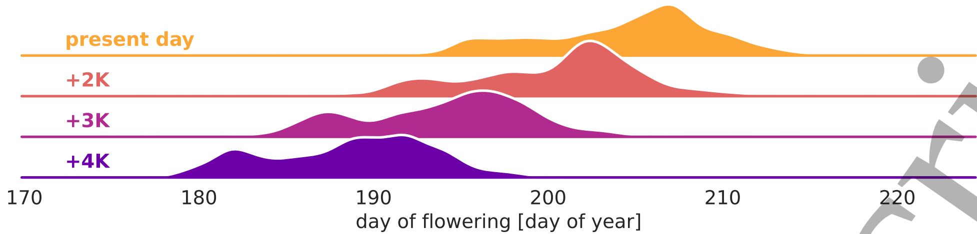

Figure 6: Frequency distribution of flowering dates of maize over the European domain for the different storylines scenarios (present day, +2K, +3K and +4K).

have diverging effects in different years. Our analysis identifies southeast Europe as a climate change hot spot, warranting a closer analysis. The mean HSI over southeastern Europe shows a higher level of heat stress than the European average, resulting in a stronger reduction of the harvest index. For present day, the area affected is on average 0.8 Mha, with a mean HSI of 0.86, corresponding to a reduction of the harvest index of over 20% in southeastern Europe.

Despite 2019 having a considerable impact on HSI (0.88), only 33 kha of the harvested area was affected, leading to a weak overall impact (Figure A3). In 2021, the HSI had a much larger impact (0.76), and over ten times more area was affected (400 kha), with the main impact restricted to the eastern part of the study area. Figure 7 shows the dramatic increase in affected area when the year 2021 is transferred into +2K, +3K and +4K storyline scenarios. In the +4K storyline, there is a dramatic increase in severity, with almost all the study area affected by *severe* (33 %; 2.8 Mha) or *very severe* conditions (43%; 2.11 Mha).

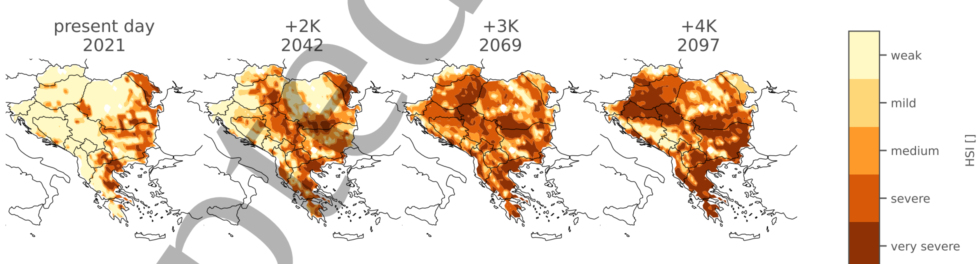

Figure 7: The Heat Stress Index (HSI) for south-eastern Europe in the heat year 2021 for the different storyline scenarios (present day, +2K, +3K and +4K).

3.5 Mitigation Strategies

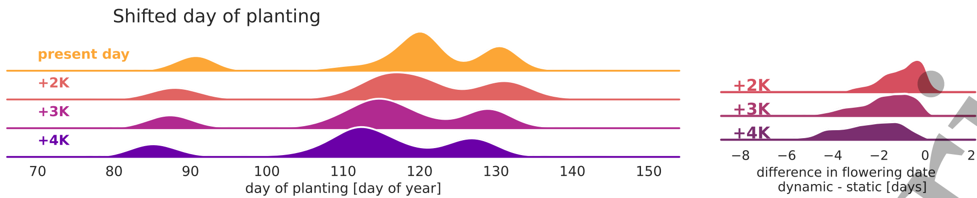

Figure 8: Left: Frequency distribution of planting dates for static and rule-based (dynamic) planting date adaption. The static planting dates from the Jägermeyr et al. 2021 crop calendar (present-day) are compared with the dynamic, storyline-dependent planting dates (+2K, +3K, +4K). Right: Differences flowering date between static and dynamic planting dates aggregated over Europe and averaged over all years (2018 - 2022).

In order to assess whether planting adaptation can help alleviate heat stress we compare the static planting dates from the Jägermeyr et al. 2021 crop calendar with the dynamically derived planting dates under future climate scenarios (see section 2.3). We applied the dynamic planting scheme to the present day scenario to compare with the static planting dates but saw no significant difference, demonstrating that the scheme does not introduce artefacts.

3.5.1 Differences due to management adaptations

Applying the dynamic planting scheme leads to a general advance of the planting day on average one week earlier compared to static planting under the +4K scenario, which in turn leads to the flowering date also being reached earlier (**??**).The effect varies between the years in the storylines, but on average anthesis is reached around two days earlier for every storyline (**??**), albeit with local differences. The north-east of Europe shows slightly later flowering under the dynamic conditions in the colder years 2017 and 2020. The differences in flowering between the dynamic and static planting dates become slightly higher with increasing warming. Some regions, such as north-east Europe and the Iberian peninsula show almost no change, while in Germany and the north of France, flowering occurs up to 10 days earlier. The earliest flowering is found in 2018 under the +4K storyline and is on average 6 days earlier than in the static planting scheme. Parts of central Europe, especially the Czech Republic, show flowering dates up to 20 days earlier.

Our results show that planting date adaptation would affect the experienced heat stress throughout most of Europe. On average, the reduction in the HSI is around 5 % relative to the static planting dates. Generally, the difference between dynamic and static planting become more significant with increasing climate change signal, with regions experiencing up to 20 % less heat stress under the dynamic planting scheme.

However, one can also see that not all of Europe experiences this alleviating effect and in many southern regions, a weather-adapted planting did not reduce heat stress at flowering. Especially in southern Europe the adjusted planting in some years even leads to a worsening of the HSI, with maize crops 10 % more stressed under the earlier planting date in the +4K scenario. However, the effect is heterogeneous between years. In 2019 and its storylines the alleviating effect is quite strong, especially in central Europe, causing up to 20% less heat stress within the +4K scenario, while 2018 and 2022 show an increase in the HSI with the dynamic planting compared to keeping the current planting dates in France and Slovenia (Figure 9).

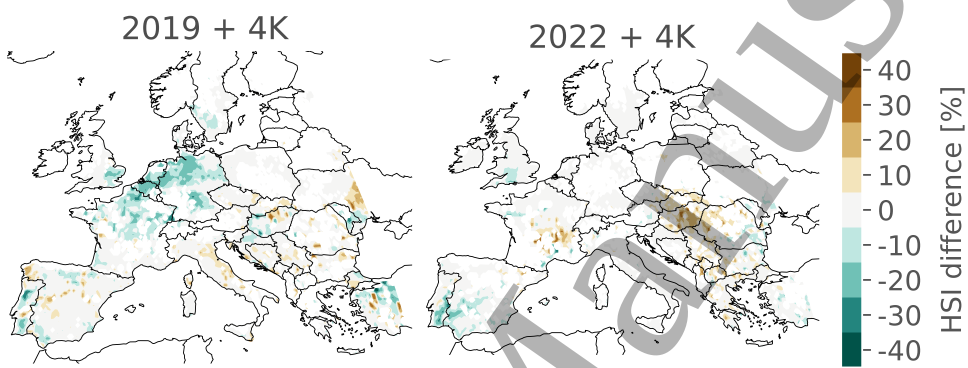

Figure 9: Differences in the Heat Stress Index (HSI) between static and dynamic planting dates in the years 2019 and 2022 of the +4K storyline. Blue color denotes less heatstress with dynamic planting, brown shows more stress under dynamic planting. The years 2018, 2020 and 2021 can be found in Figure A8.

3.5.2 Cultivar variances

While the HSI is a simplified concept to integrate the complexities of plant physiology, it is still possible to study the potential effect of cultivar adaptation. The parameters of T_{cr} can be seen as unified and simplified versions of plant genetics. By varying parameters, it is possible to give an idea of the behaviour of different cultivars. Figures A6 and A7 show that, while the absolute values of HSI differ if different T_{cr} values are used, changes vary locally. For wheat, the highest negative impact of a more sensitive cultivar is visible in France, where different varieties could make up to a 20 % difference in yield. It is also evident that spring wheat is much more susceptible to cultivar differences, whereas the differences in the winter wheat growing areas are negligible, all keeping a weak stress level. Maize also shows local behaviour, though spatially more granular compared to the modeled stress levels. By changing the anthesis stress threshold by $\pm$ 2°C, only a 5% difference in yield limitation is noticeable, much less as compared to spring wheat.

4 Discussion

In this study, we developed a framework allowing us to quantify the impact of anthesis heat stress on European crop yields during the reoccuring heatwaves between 2018-2022. Additionally, using storyline simulations, we assessed how these anomalous warm summers would have played out under an even warmer climate (+2, +3 and +4K). Our results show that the variability between years in one warming storyline is bigger than the difference between the warming storylines for both maize and wheat cropping systems. This suggests that the way a heat stress event unfolds in terms of timing and duration can be more important for agricultural production than the regional mean warming levels. Especially for maize, this is visible in both 2019 and 2022. 2019 showed some record-breaking peaks of the heatwave (Klimiuk et al. 2024), but this did not align with the plant flowering, leading to relatively low HSI levels in the present day scenario. 2022 showed some of the strongest effects of anthesis heat stress, with present-day yield losses higher than projected in the +4K storyline for 2018, despite 2018 also being considered an extreme year in terms of heat, because in 2022 the timing of the heatwave fell closer to plant anthesis. Results show that the most vulnerable areas for maize are the Iberian Peninsula, Italy and south-eastern Europe, of which south-east Europe is currently the the largest maize grower with up to 30% of a grid cell growing maize (according to MIRCA2000). Our calculation of a yield loss of around 10% for maize in 2022 is similar but slightly higher than the reported values in Baruth et al. 2022, who attribute ca 8.6% yield loss to the 2022 heatwave in Europe. One reason for this discrepancy may be that our calculations are only applicable to the rainfed cropping area, which experienced higher losses than irrigated systems.

Similar HSI-based methods have been applied by Deryng et al. 2014 and Teixeira et al. 2013 for the RCP 8.5 and A1B scenarios, showing a global doubling of yield losses due to heat stress at anthesis for maize and wheat in the last decade of the century. While their results do not show large impacts over Europe, this may be due to the choice of scenarios. While the RCP8.5 has a similar impact in regards to warming levels to the +4K storyline, extreme events are often not captured in the CMIP6 models, and even more so in previous CMIP iterations (Davini et al. 2020; Hirsch et al. 2021; Domeisen et al. 2023). Our results show that the difference between a ”normal” and an ”extreme” year can have much higher impacts on stress levels, making it easy to miss these nuances, especially on the coarser resolution of a global model. Attribution studies such as Zampieri et al. 2017 and Vogel et al. 2019 show similar patterns, with 18-43% of the variance in yields being attributed to extreme events. Furthermore, Semenov et al. 2011 highlight how in Europe heat stress is highly likely to become more important than drought stress.

The storyline approach is a physically consistent method, thus allowing us to study the consequences of recently observed extreme heat periods if they would happen in different plausible future warmer climates. Therefore, as pointed out by Shepherd et al. 2018, this methodology provides a very effective way of making the impacts of climate change more tangible not only for experts but also for the general public and stakeholders (e.g. politicians, media, etc), thus facilitating decision-making in adaptation and mitigation. However, it does have the drawback of not producing probabilistic predictions. As such, changes in likelihood are out of the scope of this methodology. However, it is known from other methods that an increase in extreme events is highly likely (Trnka et al. 2014). Furthermore, since only few models have performed nudged storyline simulations, we were only able to work with data from one model chain (AWI-CM1 with ICON-CLM). In the future, we hope that the method is applied more frequently, thus making model-ensembles possible. For now we are happy to be able to present the whole modelling chain from global scale modelling (Sánchez-Benítez et al. 2022), to downscaling (Klimiuk et al. 2024) to direct impact analysis on agriculture.

Our findings also highlight how important the differentiation between spring and autumn sown cultivars will become in the future. While winter wheat can cope fairly well with warmer years due to its phenological advantage , spring wheat and maize are already vulnerable to anthesis stress, which will only worsen in the future (Webber et al. 2018) (for flowering dates see Figure A5). The warming-induced reduction of the area suitable for winter wheat thus exacerbates the problem of anthesis heat stress since it makes agriculture more dependent on spring-sown wheat, which is more susceptible to heat stress during the anthesis phase.

One striking result is that the alleviation of heat stress due to planting date adaption was heterogeneous between the years. When the heatwaves occur mainly in summer, like in 2019, the planting date adaptation is most effective. If the heatwaves were instead due to an extended blocking situation starting earlier in the year, like in 2018 or 2022 (Kueh et al. 2020), an adaptive planting that only looks at sowing-time conditions sometimes leads to an increased anthesis heat stress, if it happens to shift the flowering period into alignment with the heatwave. In 2019 the heatwave above central Europe peaked only in June, whereas in 2018 and 2022 it was already warm throughout May. This means that simply looking at the current conditions for sowing might not be sufficient to ensure a secure harvest in the future. Trnka et al. 2014 also argue that earlier planted crops often have a reduced global radiation available, reducing the yield potential of these crops. However, earlier planting could open up the possibility of multi-cropping (Iizumi et al. 2019; Waha et al. 2020), which might be able to balance out the effect of reduced global radiation (Porter et al. 2014), but with the drawback of increased evapotranspiration. These findings highlight the need for improved seasonal forecasting since there is still low reliability in predicting European heatwaves using seasonal forecasts (Weisheimer et al. 2011; Prodhomme et al. 2022; Domeisen et al. 2023). Since we did not see significant yield cuts to winter wheat due to anthesis heat stress, we did not apply the adaptation of planting dates to winter wheat. Murakami et al. 2024 developed an improved version of the Iizumi et al. 2019 crop calendar specifically for winter wheat, which showed earlier flowering despite later planting dates under warmer climates, further showing the potential in winter cultivars for evading anthesis heat stress.

Heat stress is not the only important factor that might increase under climate change. As a side effect of temperatures getting hotter and planting dates shifting earlier under climate change, the danger of late frosts may become more unpredictable. While currently farmers planting after the cold periods in early spring still have sufficient season length to get a good yield from their crop, as temperatures get higher planting dates not only can but need to be shifted earlier to get sufficient yields or to be able to grow a second rotation, compensating for the lower yields of the single crop. While the risk of late spring frosts is likely to increase (Trnka et al. 2014), the risk is comparatively low when looking at the risk of anthesis heat stress.

Southern Europe, specifically the Mediterranean region, have shown higher warming (Perkins-Kirkpatrick et al. 2020; Cos et al. 2022) and drying (Samaniego et al. 2018) levels than the rest of Europe, proving it to be a climate change hot spot (Lionello et al. 2018). This creates a feedback loop where the lack of moisture causes a shift towards more latent energy (Miralles et al. 2019) leading to moisture-limited regions like the Mediterranean are heating up even quicker (Perkins 2015; Seneviratne et al. 2021). Brás et al. 2021 show that yields have already seen large impacts in southern Europe during past heatwaves, which is in line with our results for the present-day scenario. While in 2021 the effect of heat stress was already quite noticeable, the interaction of this type of heatwave with climate change has extensive effects. The *severely* affected area under the +2K scenario coincides with the Danube plains, which are some of the most highly harvested areas in Europe. While other regions of Europe might seem to be similarly affected (Figure 3), not all highly affected areas are major cereal producers. In the Mediterranean region, we find that earlier planting could also not improve heat stress for spring-sown crops. Moriondo et al. 2011 show similar results for sunflowers, as the plant development cannot be advanced enough in spring to avoid heat stress periods. Ludwig et al. 2010 showed that there is also no benefit on yields, since the lower initial biomass limits grain yields. In their assessment of yield reduction with anthesis heat stress for durum wheat in the Mediterranean, Moriondo et al. 2016 show a decrease of 9% in Spain and 5.1% in Greece. This is comparable with the HSI of 0.93 (meaning a 7% decrease in the harvest index) in the southeast of Europe in a non-extreme year (2017) of our +2K scenario. However, we also see that the extreme years in the same warming scenario have a much higher HSI value between 0.75 to 0.86 (Figure 7), though these values need to be taken with caution due to the slight overestimation of T_{max} in the ICON model close to the black sea (Klimiuk et al. 2024). The IPCC dedicated a special chapter to the Mediterranean in their last report, synthesizing that wheat yields under rainfed conditions could decline up to 59% and that decreases are also expected for maize due to a shorter growing season length (Ali et al. 2022).

What we explicitly did not do in this study is calculate potential yields. The purpose of the HSI is to give a clear picture of one stressor, specifically heat stress due to high temperatures at flowering. While Deryng et al. 2014 and Teixeira et al. 2013 normalize for yields, we believe that normalizing with yield introduces more uncertainties than normalizing over the harvested area. The harvested area in a region is representative of more fixed state parameters, such as soil and location. Yield also depends on many other stresses, such as nutrient stress, drought stress or extreme precipitation. Modelling yield failures under current conditions already poses a large challenge in disentangling the sources (Webber et al. 2020). These factors are also subject to change with climate change, making it difficult to isolate the impact of heat stress alone. We also did not consider the effect of CO_2 fertilization in this work. While this is a strong determinant of the balance of future crop yields, multiple studies show that it is also still one of the largest uncertainties in crop modelling (Müller et al. 2021). It is quite certain that CO_2 will have an alleviating effect on the otherwise negative impacts of climate change (Schauberger et al. 2017; Jägermeyr et al. 2021), however, the predictions are not conclusive enough to show that it will be sufficient to compensate for yield losses, especially in the context of (multiple) extreme events (Bezner Kerr et al. 2022). Generally, wheat, being a C3 plant, is expected to profit more from increased CO_2 than maize (Jägermeyr et al. 2021). However, yield increases often coincide with a loss of nutritional value, and therefore do not add to food security (Mbow et al. 2022). Another uncertainty lies in the thresholds used for the specific crops. While there is extensive research on the physiological reaction of crops to heat shocks (Wahid et al. 2007; Akter et al. 2017; Farooq et al. 2011; Rezaei et al. 2018), the results are not directly transferable as one threshold per crop (Rezaei et al. 2015). Multiple papers apply the same approach, but each uses a different threshold per crop (Deryng et al. 2014; Teixeira et al. 2013). While this type of model only conceptually accounts for different plant cultivars, the notion of heat stress tolerant and sensitive cultivars is based on wheat genetic background (Browne et al. 2021). Our comparison of applying different threshold temperatures shows that there could be a larger spread in the potential impact. Zabel et al. 2021 also find that a redistribution of current cultivars can offset climate change effects up to 2°C, and after that new cultivar adaptations need to be found, emphasizing the need for fast breeding strategies.

Of course, heatwaves do not only negatively affect crops with high temperatures at anthesis, periods of high temperatures often lead to low soil moisture and therefore drought stress (Strer 2020; Fahad et al. 2017; Webber et al. 2018). Additionally, the low soil moisture creates a positive feedback loop, exacerbating the temperature increase on both a regional scale (Tripathy et al. 2023; Bevacqua et al. 2024; Xoplaki et al.

2023), but also at the canopy level (Webber et al. 2016). Combining the storylines with a full process-based crop model also including soil moisture dynamics could therefore add to the understanding of the full scale of the impact of heatwaves under climate change. Also, other extremes, such as late frosts or extreme rainfall, can have detrimental impacts on crop production (Lesk et al. 2016; Schmitt et al. 2022; Beillouin et al. 2020), which could warrant a future analysis into specific events captured in the storylines.

5 Conclusion

We have studied the effects of anthesis heat stress on European cropping systems. By employing a heat stress index method to analyse the reoccurring heatwaves between 2018 to 2022 and its projections under climate change (+2K, +3K, +4K) we show that anthesis heat stress will become more important through the century as heatwaves become more frequent and intense. As winters become warmer, the area where winter wheat can be potentially be grown with sufficient vernalization would diminish, leading to a higher need for spring sown cultivars. These however are much more prone to experience anthesis heat stress, as they do not have a growth advantage in spring, leading to later flowering and therefore making high temperatures during anthesis more likely. Our findings underscore that the timing and intensity of a heatwave outweigh the underlying climate change signal, emphasizing the importance of accurate seasonal forecasting and understanding heatwave dynamics for effective management adaptations. Especially in the southern regions of Europe anthesis heat stress will gain importance, especially in a heatwave situation similar to that of 2022. Additionally, our study suggests that moving the planting date earlier may not always be beneficial, highlighting the complexity of mitigating heat stress impacts in agricultural systems.

Competing interests The contact author has declared that none of the authors has any competing interests.

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Data & Code Availability The simulations are stored on the supercomputer Levante at the German Climate Computation Center (DKRZ, Hamburg) and will be made available online upon completion of the data preparation. The scripts for calculating the heat stress and plotting the data are available at https://codebase.helmholtz.cloud/lioba.martin/scenic-heatstress

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Appendix A Supplementary Materials

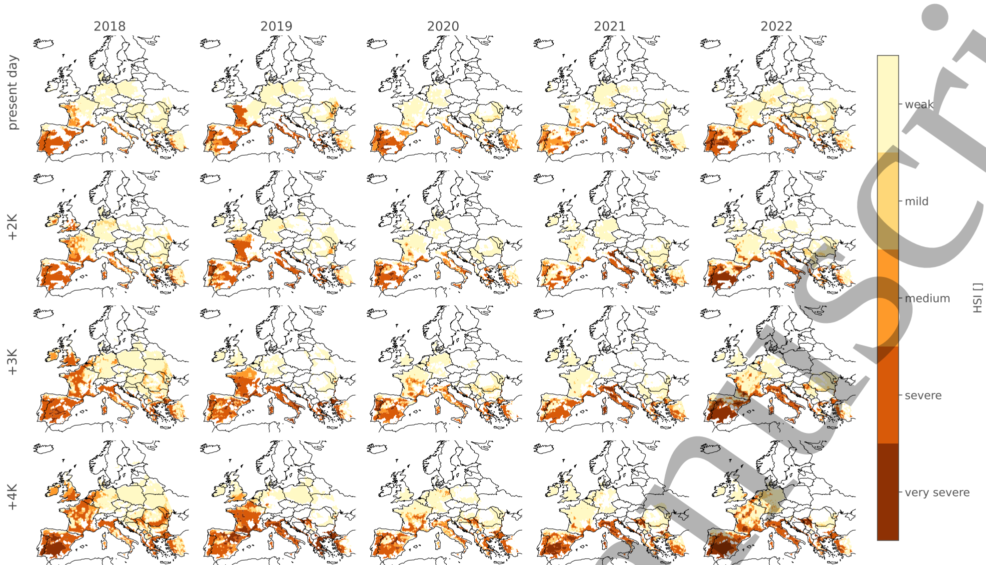

Figure A1: Heat Stress Index (HSI) for wheat anthesis heat stress ($T_{cr} = 25°\text{C}$), which is both winter and spring wheat combined. HSI values are grouped by increments of 0.1 from 0.5 to 1, as 0.5 was the largest observed impact. The potential yield reduction per pixel corresponds to 1 - HSI.

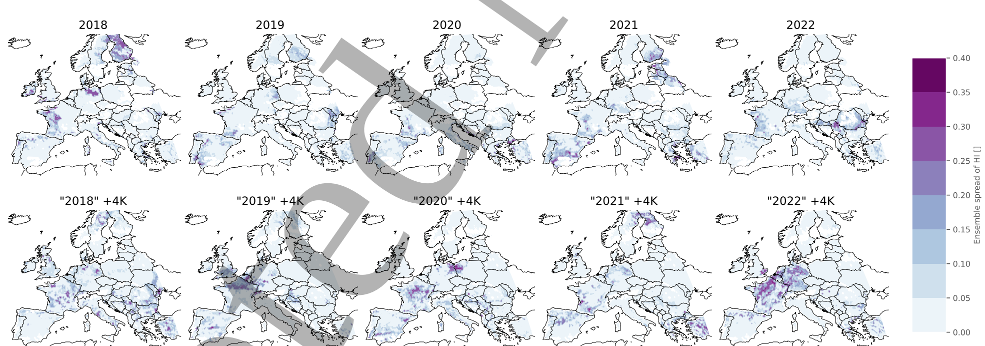

Figure A2: Spread of the wheat Heat Stress Index (HSI) in the present day and +4K scenario for all ensemble members. Mann-Whitney U test showed no significant differences between ensemble members ($p < 0.05$).

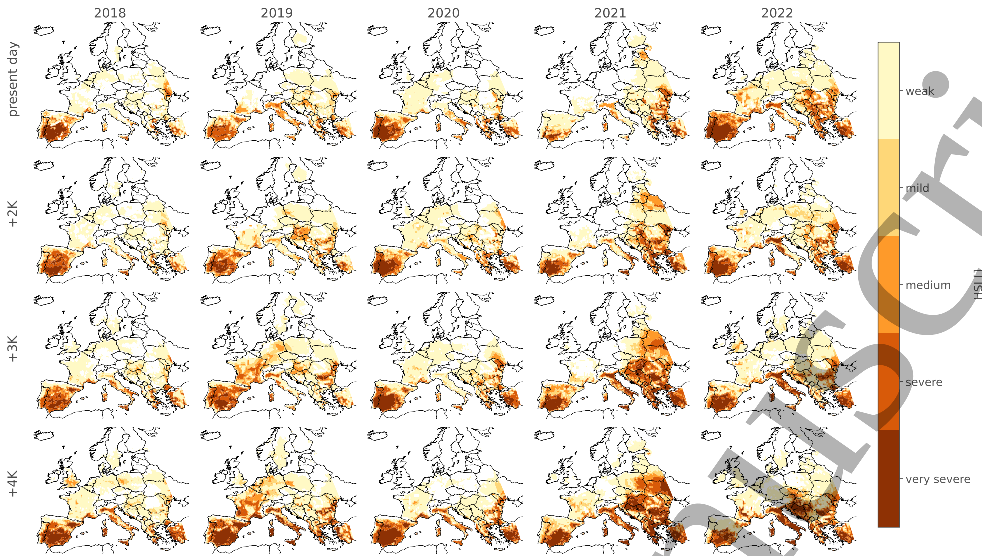

Figure A3: Heat Stress Index (HSI) for maize anthesis heat stress ($T_{cr} = 32°\text{C}$), values are grouped by increments of 0.1 from 0.5 to 1, as 0.5 was the largest observed impact. The potential yield reduction per pixel corresponds to 1 - HSI.

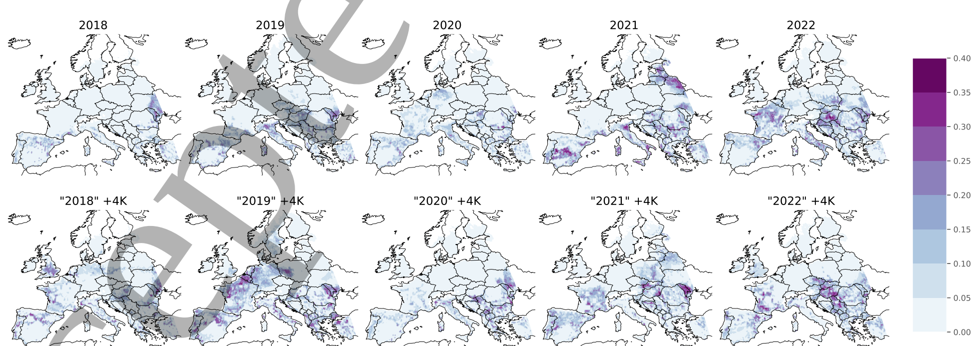

Figure A4: Spread of the maize Heat Stress Index (HSI) in the present day and +4K scenario for all ensemble members. Mann-Whitney U test showed no significant differences between ensemble members ($p < 0.05$).

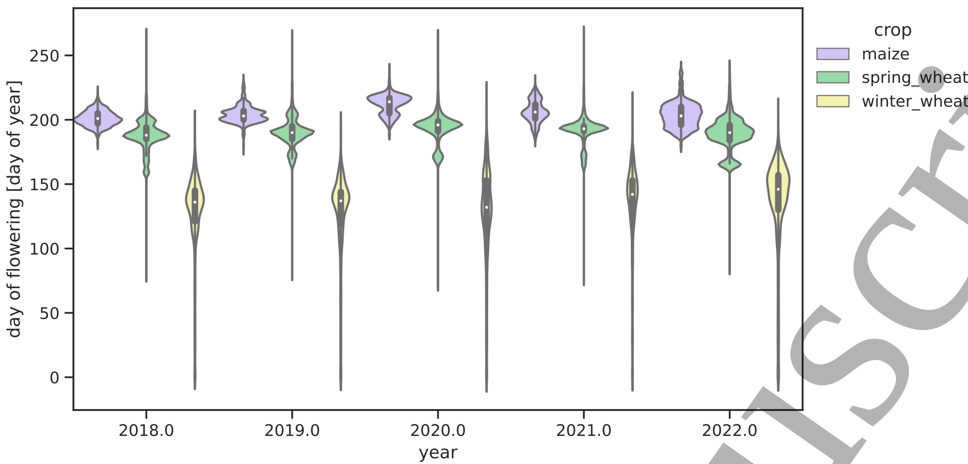

Figure A5: Day of the year where flowering occurs in maize, spring wheat and winter wheat throughout Europe.

Table A1: Harvested area in million hectares for the different levels of heat stress in south-eastern Europe.

year	very severe	severe	strong	moderate	weak	none
2021	0.40	1.31	0.48	0.62	3.65	0.07
2042	1.12	1.70	0.97	1.34	1.32	0.02
2069	2.11	2.46	0.91	0.63	0.34	0.00
2097	2.78	2.15	0.42	0.66	0.43	0.00

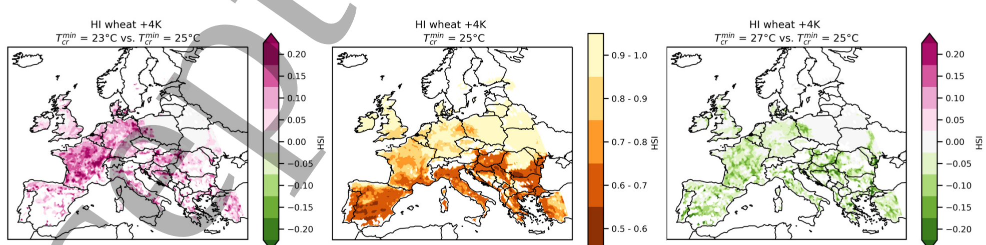

Figure A6: Differences in the Heat Stress Index (HSI) index between different threshold values used in wheat. Left: Difference between the "default" T_{cr} and T_{cr} -2K, the HSI for the default setting and the T_{cr} +2K.

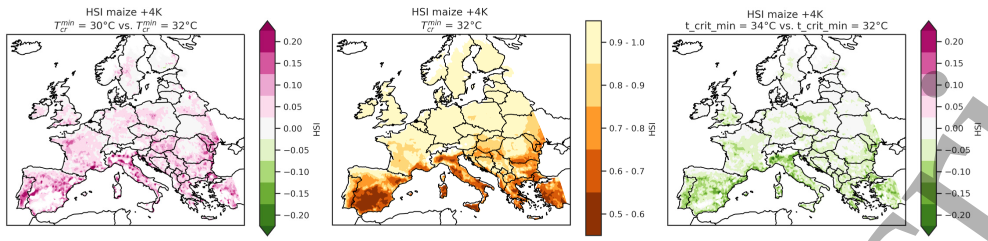

Figure A7: Differences in the Heat Stress Index (HSI) index between different threshold values used in maize. Left: Difference between the "default" T_{cr} and T_{cr} -2K, the HSI for the default setting and the T_{cr} +2K.

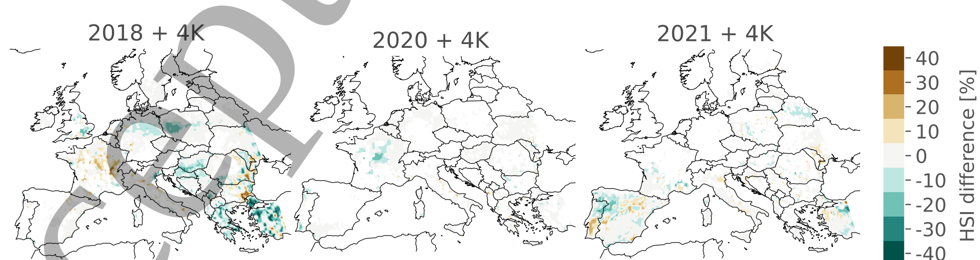

Figure A8: Differences in the Heat Stress Index (HSI) between static and dynamic planting dates in 2018, 2020 and 2021 of the +4K storyline.