



Critical increase in the occurrence of heat stress during reproductive growth in Russian wheat beyond 1.5 C global warming

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ABSTRACT

Exposure to a critical high temperature during the reproductive period can harm wheat development, entail yield losses and lead to yield instability. In the recent past, Russian wheat production suffered a few times from marked downturns caused by heat waves that eventually had repercussions on the global wheat market. In this study, we assess the frequency of heat stress days on Russian spring and winter wheat production using climate scenarios generated from five general circulation models and reflecting four emission scenarios. We find that the fraction of cultivated area characterized by a significant positive trend in risk increases sharply if global warming exceeds 1.5 °C targeted by the Paris Agreement. Currently particularly affected areas are the main cultivation regions in the southern Urals and southern Siberia (spring wheat) and southern European Russia (winter wheat). In scenarios not foreseeing mitigation, conditions comparable to those experienced in 2010, considered here as a critical year, could become rather common in the future. We estimated that the probability of incurring in a critical year within a 30-year time window could reach 40–60% (spring wheat), respectively 20–40% (winter wheat) during the second half of the century, over most of the Russian territory. Our analysis suggests that expansion of the cultivation area towards more northern latitudes is not sufficient to prevent risk associated with heat waves, suggesting the need for other measures of adaptation to sustain production and stabilize yield.

1. Introduction

Recent scientific assessments (IPCC, 2014) and reviews (Ruane et al., 2018) express concern about the challenges imposed by climate change on agricultural yields (Challinor et al., 2014; Trnka et al., 2014) and food security (Dillard, 2019; Godfray et al., 2010). Recent climate trends already increased yield variability of staple crops (Ray et al., 2015; Vogel et al., 2019) and the volatility of world crop prices (Chatzopoulos et al., 2019). Climate change has weakened global wheat yield progress (Lobell and Field, 2007) and limited global wheat production (Asseng et al., 2015; Chatzopoulos et al., 2019). While factors other than climate, in particular the choice of cultivars (Anderson, 2010) and field management options (Anwar et al., 2013), contributed to enhance crop yields (Goudriaan and Zadoks, 1995), wheat production remained vulnerable in particular to heat waves and drought (Semenov and Shewry, 2011; Zampieri et al., 2017). In Europe, the summer of 2003 exceeded the 1901–1995 long term average by at least 2 °C and it was warmer than any other summer back to 1500 (Luterbacher et al., 2004). At the global scale, the summers of 2005, 2007, 2010 and 2011 were

warmer than those of all prior years back to 1400 (probability $P > 0.95$) (Tingley and Huybers, 2013). Model results show that the percentage of global area affected by heat waves has increased in recent decades (Russo et al., 2014) and heat waves will become more intense, more frequent, and longer lasting in the second half of the 21st century (Meehl and Tebaldi, 2004; Russo et al., 2017).

Without adaptation, climate change is expected to have significant negative impacts (medium confidence) on staple crops (wheat, rice, and maize) in tropical and temperate regions alike, if local temperature increases by 2 °C or more above late-20th-century levels (Challinor et al., 2014; Porter et al., 2014; Schleussner et al., 2018; Hurlbert et al., 2019). Gourdjji et al. (2013) argued that by the 2030s 11% of wheat global harvested could be exposed to physiologically critical temperatures for at least five reproductive days on average every year.

In Russia, good grain harvests achieved during the last decades led to grain surplus, allowing the country to substantially increase its wheat export (USDA, 2018; Wegren, 2018). Nevertheless, climate had a net negative impact of the order of 15% (Lobell et al., 2011) to 20% (Anderson, 2010) on the progress of Russia's wheat production. At the

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same time, Russian wheat has remained vulnerable to adverse weather conditions, in particular heat waves, droughts and episodes of excess precipitation (Chatzopoulos et al., 2019; Zampieri et al., 2017). Regional yield statistics by the Russian Federal State Statistics Service (ROSSTAT, 2015, 2014) indicate an overall coefficient of variation of 20–30% in winter wheat, and of 30–40% in spring wheat for the period of 1996–2015. In Southern European Russia (the main winter wheat cultivation area), as well as in the southern Urals and southern Siberia (the key areas for spring wheat production) heat stress during reproductive growth has been responsible for a large fraction of the observed yield variability (Giannakaki and Calanca, 2019). Hauser et al. (2016) showed that the dry 2010 soil moisture alone has increased the risk of a severe heat wave in western Russia sixfold, while climate change from 1960 to 2000 has approximately tripled it. The record-breaking heat wave of 2010 affected 17% of the total crop area and ravaged Russia's wheat crops (Barriopedro et al., 2011; Diffenbaugh et al., 2017; Wright et al., 2014) to such an extent as to force the Russian government to ban grain exports (Welton, 2011). In the Volga region, the onset of drought conditions in spring (Cherenkova et al., 2015) exacerbated the negative impacts of the heat wave (Wegren, 2011).

A more frequent exposure to heat stress during the reproductive period as a consequence of global warming has the potential to destabilize Russian wheat yields further, with implications for the global market (Welton, 2011). Knowledge of how different emission pathways can change the risk of heat stress in both spring and winter wheat production is therefore of the utmost importance for informing agriculture and for developing adaptation strategies to promote yield stability. Here, we use a set of five climate scenarios issued from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP; Warszawski et al., 2014) to assess both the presence of a significant positive trends in the frequency of heat stress days around flowering, as well as the probability of critical years, i.e. years with heat stress conditions comparable to those observed in 2010. The scenarios embody all four Representative Concentration Pathways (RCPs; van Vuuren et al., 2011). Although other stress factors, abiotic but also biotic, can impair wheat development and limit yield formation (Gate, 1995), heat shocks affecting grain formation at anthesis (Akter and Rafiqul Islam, 2017) are considered as being most adverse. For this reason, wheat exposure to damaging temperatures around flowering has been in the focus of a number of studies published in recent years (e.g. Semenov and Shewry, 2011; Gourdjji et al., 2013; Teixeira et al., 2013) and represents the central topic of the present investigation.

To allow for adjustments in the seasonality of sensitive developmental stages of wheat, we dynamically infer the date of the

reproductive stage by means of the phenological model proposed by Olesen et al. (2012). This model has already supported earlier impact assessments (e.g. Trnka et al., 2014). Considering the results for various emission scenarios helps highlighting the most vulnerable regions within Russia's wheat cultivation area. Adopting 2010 as a benchmark, we finally show how the probability of exceeding current extreme conditions will evolve as a function of warming. This enables us to examine in a quantitative way whether limiting global warming to 1.5 °C can reduce the risk for today's extremes to become the norm in the future.

2. Materials and methods

2.1. Daily weather data (1981–2014)

As in Giannakaki and Calanca (2019) we obtained daily data for daily minimum (T_{\min}), and maximum temperature (T_{\max}), as well as daily precipitation amounts (Pr) spanning the years 1981–2014 for 118 land-based weather stations (Fig. 1) distributed across the wheat production area of Russia (Monfreda et al., 2008). We extracted the data for the period 1980–2009 from the Carbon Dioxide Information Analysis Centre (CDIAC) data repository (<https://www.zotero.org/google-docs/?Khl3vK Bulygina and Razuvaev, 2012>), and resorted to the database maintained by and the Federal Service of Hydrometeorology and Environmental Monitoring (<http://www.meteorf.ru/>) concerning the data for the period 2010–2014.

2.2. Climate scenarios

We employed trend-preserving, bias corrected climate scenarios (ISIMIP 2b) at $0.5^\circ \times 0.5^\circ$ horizontal resolution provided by the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) (Hempel et al., 2013; Warszawski et al., 2014). We extracted daily data for mean, minimum and maximum temperature spanning 1980–2099 from the output of following five Global Climate Model (GCM) of the fifth phase of the Coupled Model Intercomparison Project (CMIP5): GFDL-esm2m, HADGEM2-es, IPSL-CM5a-Ir, MIROC-esm-chem, NORESM1-m (Supplementary Information). Scenarios were available for all four RCPs, namely RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5 (van Vuuren et al., 2011).

To obtain corresponding changes in global mean temperature (ΔT_{gl}) for each combination of emission scenario and GCM, we manually digitized Fig. 1 in Warszawski et al. (2014), making sure that our readings had an accuracy of $<0.2^\circ\text{C}$. According to Warszawski et al. (2014), the data presented in that figure are “changes in [global mean

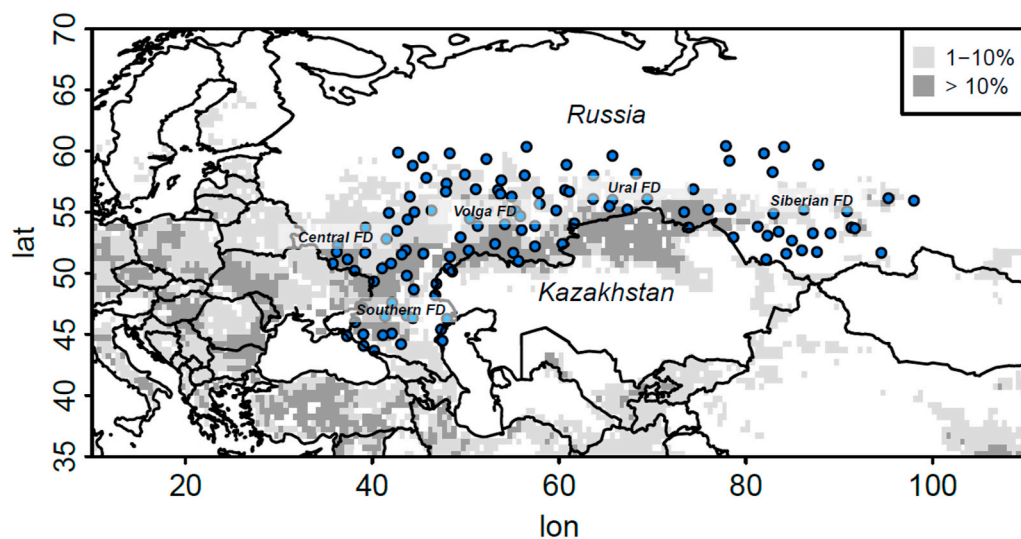


Fig. 1. Map of the study region, showing in blue the location of the 118 weather stations used for this study and, in the background, the wheat cultivation area. The latter represents the harvested area as compiled for the year 2000 by Monfreda et al. (2008). The original longitude/latitude resolution of the data is 5-arc-minutes \times 5-arc-minutes (~ 10 km by 10 km). For plotting purposes, we aggregated the data on a 0.5-degree \times 0.5-degree grid and expressed the harvested area as percentage of the grid-cell area (light grey: 1–10%; dark grey: $> 10\%$). Also indicated on the figure are the approximate location of Russian Federal Districts (FD) mentioned in the text. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

temperature] with respect to the 1980–2009 average, averaged over 30-year window, centered on [the] year shown”. Hence, we considered the values for e.g. 2085, the last year in the record of [Warszawski et al. \(2014\) Fig. 1](#), as representing the time frame 2070–2099.

2.3. Phenological phases

We followed [Olesen et al. \(2012\)](#) to estimate the duration of phenological phases. The underlying assumption of this model is that agriculture adopts wheat varieties with thermal requirements that match the long-term mean temperature conditions of a given site. Although not including data from Russia, the model was developed using data from a wide latitudinal range that can be assumed to represent a significant fraction of the wheat varieties cultivated today in Europe ([Olesen et al., 2012](#)). It was shown in the study of [Giannakaki and Calanca \(2019\)](#) that the model performs reasonably well with respect to both the sowing dates of spring wheat as well as the flowering dates of spring and winter wheat.

2.4. Frequency of heat stress days around flowering and trend test

Various abiotic and biotic stresses affect wheat development and yield formation. Drought sensitive stages occur along the growing season, from elongation to flowering and grain filling ([Dodd et al., 2011](#)). Heat stress, on the other hand, is particularly harmful during anthesis ([Semenov and Shewry, 2011](#); [Prasad and Djanaguiraman, 2014](#)), and it is for this reason that in this work we focus on heat stress occurrence around the time of flowering.

We evaluated the frequency of heat stress days around flowering (f_{HS}) ([Semenov 2009](#)) according to [Giannakaki and Calanca \(2019\)](#) and following the approach proposed by [Teixeira et al. \(2013\)](#). We first calculated, for each day d within a 31-day window around flowering, a daily heat stress indicator, $I_{HS}(d)$, as:

$$I_{HS}(d) = \begin{cases} 1 & \text{if } T_d(d) > T_{crit} \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where $T_{crit} = 27^\circ\text{C}$ is a critical threshold ([Teixeira et al., 2013](#)), and $T_d(d)$ is the daytime mean temperature, i.e. the average temperature for daylight hours. We evaluated the latter from $T_{min}(d)$ and $T_{max}(d)$, the daily minimum and maximum temperatures, by using an analytical approximation to the diurnal temperature cycle ([Felber et al., 2018](#)), which we integrated from sunrise to sunset ([Giannakaki and Calanca, 2019](#)). The reason for using $T_d(d)$ rather than $T_{max}(d)$ to define $I_{HS}(d)$ is that the former is a better proxy for the temperature experienced by the crop during flowering ([Teixeira et al., 2013](#)).

Given (1), we evaluated the (relative) frequency of heat stress days around flowering as:

$$f_{HS} = \frac{1}{31} \sum_{DOY_{fl}-15}^{DOY_{fl}+15} I_{HS}(d) \quad (2)$$

where DOY_{fl} is the day of the year at which flowering is expected to take place, according to the phenological model described above.

We computed f_{HS} for each year in the records and assessed the presence of a statistically significant positive trend by means of the Mann-Kendall trend test (Supplementary Information).

2.5. Probability of critical years

Bearing in mind the impact that the heat wave of 2010 had on Russian wheat production, we assumed that the frequency of heat stress days around flowering computed for 2010 can be seen as a threshold for defining what we call a critical year. Accordingly, we estimated the probability of critical years as the relative number of years within a 30-year time window for which the frequency of heat stress days around

flowering was at least as high as in 2010.

Although the ISIMIP scenarios are bias corrected ([Hempel et al., 2013](#)), the threshold needed to define the probability of critical years in the context of these scenarios may not be the same as the one obtained for 2010 from evaluating the frequency of heat stress days around flowering based on observed weather data. In a first step, we therefore determined, for each scenario, climate model and weather station individually, the value of the f_{HS} index giving the same probability of critical years over the baseline period 1991–2020 as in the evaluation based on observed weather data. Once this done, we gauged the probability of critical years for sequential 30-year time windows running from 1992 to 2021 to 2070–2099 as the relative frequency of years characterized by a f_{HS} exceeding this threshold.

3. Results

Results of the Mann-Kendall test ([Fig. 2](#)) indicate little changes over time in the frequency of heat stress days around flowering for RCP 2.6, but clear positive trends in southern Siberia (spring wheat) and the Central Federal District (winter wheat) for RCP 4.5. Statistically significant, positive trends consistently emerge across the Russian territory for RCP 6.0 and RCP 8.5. Regions where the signal is particularly coherent (at least three out of five scenarios) are the Volga Federal District, the southern Urals and southern Siberia for spring wheat, and the Central Federal District and southern Siberia for winter wheat. They largely correspond to the present-day main cultivation areas. On average across sites and model chains, the frequency of heat stress days around flowering in spring wheat increase from 0.09 in 1991–2010 to 0.13 (RCP 2.6), 0.18 (RCP 4.5), 0.18 (RCP 6.0) and 0.23 (RCP 8.5) in 2070–2099. For winter wheat, the frequency of heat stress days around flowering increased from 0.04 in 1991–2010 to 0.05 (RCP 2.6), 0.07 (RCP 4.5), 0.08 (RCP 6.0) and 0.09 (RCP 8.5) in 2070–2099. This suggests a doubling of the frequency of heat stress days around flowering for RCP 6.0 and RCP 8.5 for both wheat types.

The relatively modest increase in the frequency of heat stress days around flowering seems at first surprising, given that across the study area the increase in annual mean temperature is roughly 1.5 times as high as the increase in global mean temperature ($\Delta M_a = 0.43 + 1.53 \Delta T_{gl}$, $R^2 = 0.96$) (see also Supplementary Information, [Fig. S3](#)). However, one should bear in mind that the an earlier occurrence of flowering entails a net cooling that partially offsets the warming induced by climate change, an issue already taken up by [Rezaei et al. \(2015\)](#). We estimated this cooling as amounting to -2°C for a 10 days earlier date of flowering., and Our scenarios suggest that, by the end of the century, on average across sites, spring wheat flowering could take place 7 (RCP 2.6) to 20 days (RCP 8.5) earlier than today, with corresponding figures for winter wheat being in the range 2 (RCP 2.6) to 10 days earlier (RCP 8.5) (Supplementary Information, [Fig. S5](#)). These figures reflect the structure of [Olesen et al. \(2012\)](#) phenology model, which assumes that the temperature sum demands of the considered growth phases depend on the long-term mean annual temperature, but that the optimal temperature for sowing of spring wheat only depends on latitude. Higher temperature demands in a warmer climate, introduced by [Olesen et al. \(2012\)](#) to account for the choice of adapted varieties, imply that the advance in the date of flowering disclosed by our results is not as clear as under the assumption of constant heat requirements. Note further, that keeping the flowering date fixed would have resulted in a much more pronounced increase in the frequency of heat stress days around flowering, (Supplementary Information, [Fig. S4](#)).

In terms of frequency of heat stress days around flowering, the 2010 heat wave represented an anomalous event at many locations ([Fig. 3](#)). Although the absolute values were not particularly high in the case of winter wheat, the corresponding 1980–2014 probability of critical years was ≤ 0.2 for both wheat types.

According to the scenarios, the probability of incurring in critical

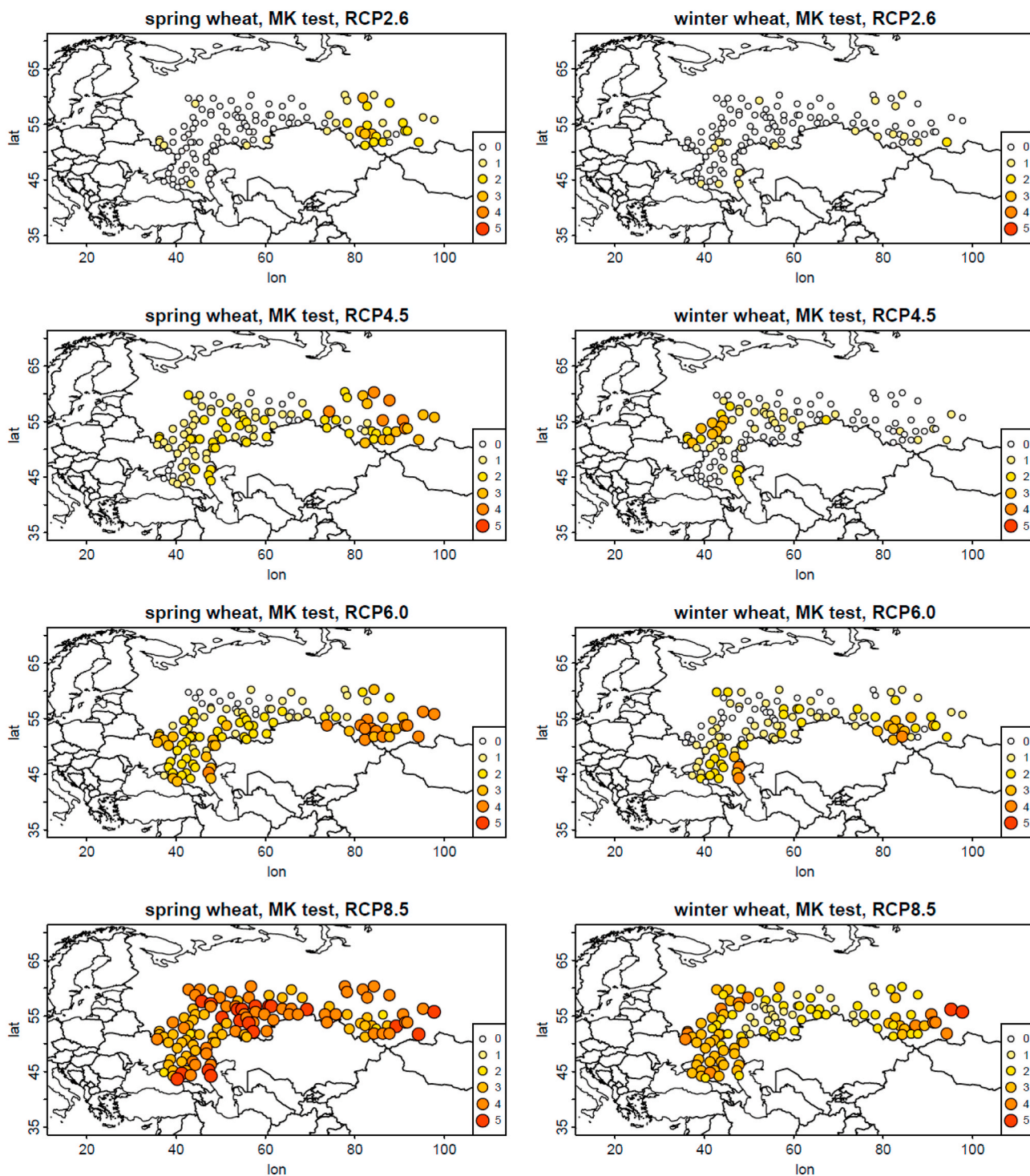


Fig. 2. Number of climate scenarios (out of five) indicating the presence of a significant increase in the frequency of heat stress days around flowering according to the Mann-Kendall trend test.

years, i.e. years comparable to 2010 in terms of frequency of heat stress days around flowering, could increase noticeably in the future, in particular if no effort is undertaken to stabilize global greenhouse gas emissions (Fig. 4). This raises the question on when action should be taken, at the latest, to protect Russian wheat production. Vaguely akin of the concept of time of emergence (Hawkins and Sutton, 2012), but adopting a point of view better suited to the present context, we defined a time of action as the time when the probability of critical years, on average across sites, becomes twice as high as during the reference

period (1991–2020). The rationale is that, by then, situations with comparable (negative) impacts on Russian wheat production as the 2010 heat wave would occur in more than 30% of the years. This is never the case under the assumptions of the RCP 2.6. However, our results suggest that the time of action could arrive between 2040 (RCP 8.5) and 2060 (RCP 4.5 and RCP 6.0) in spring wheat cultivation, and around 2050 (RCP 8.5) in winter wheat (Fig. 4).

Regions that are likely to face a sharp increase in the probability of critical years again align with today’s cultivation areas, and include the

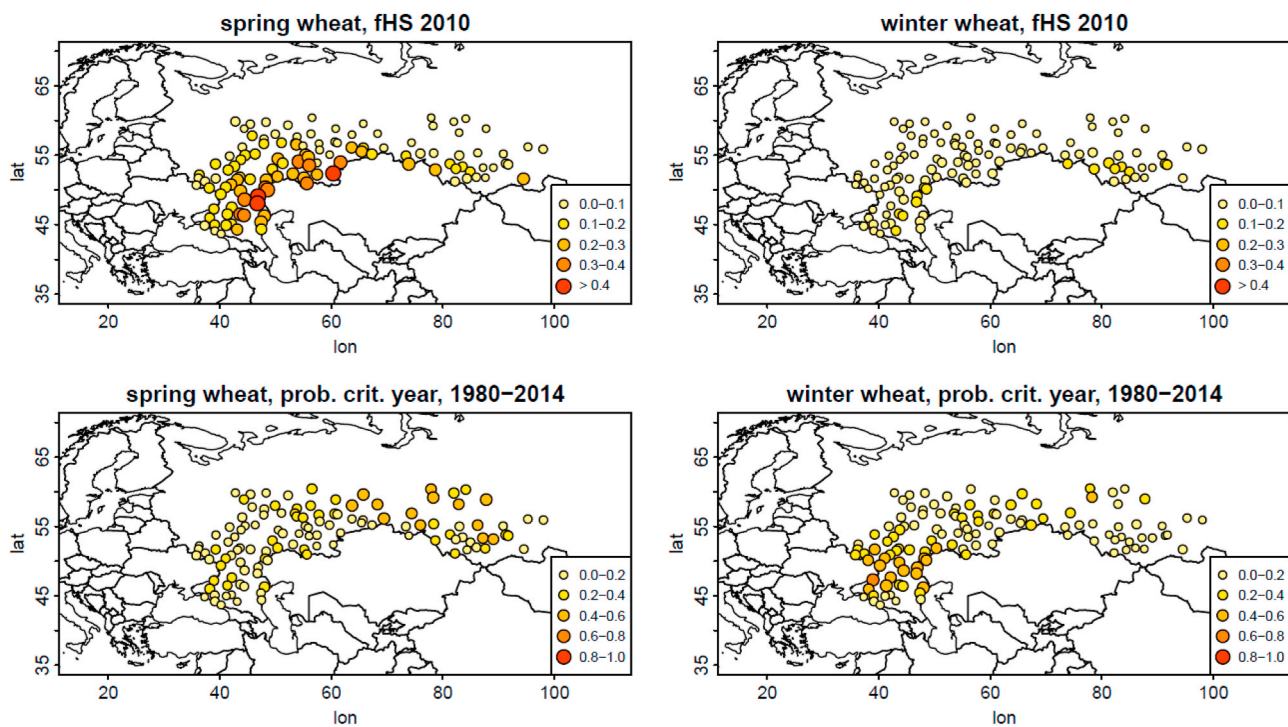


Fig. 3. Frequency of heat stress days around flowering (f_{HS}) calculated for 2010 using observed weather data (top) for spring (left) and for winter wheat (right), and corresponding 1981–2014 probability of incurring in a critical year (bottom).

Volga Federal District, the southern Urals and southern Siberia (spring wheat), as well as the Southern Federal District (winter wheat) (Fig. 5).

In the long term (2070–2099), a global warming signal transcending $+1.5^\circ\text{C}$ would imply, for spring wheat (Fig. 6, left), at least a twofold increase in the probability of critical years (Fig. 6a), on average across sites. For the most pessimistic scenarios (RCP 8.5), even probabilities of critical years of about 0.7 could be possible (Fig. 6). This indicates that situations comparable to those witnessed in 2010 could actually occur almost every year in such a future scenario. Also disclosed by Fig. 6 (right panel) is the fact that winter wheat would benefit more than spring wheat from an earlier occurrence of flowering during the season. Yet, our results suggest that even winter wheat cultivation could face significant shortfalls caused by heat stress in 30% of the years, on average, if the increase in global temperature outruns the 1.5°C foreseen by the Paris Agreement.

4. Discussion

Recent climate trends have already put pressure on Russia's grain production (Lobell et al., 2011; Welton, 2011). At the same time, the recurrence of adverse conditions, as was the case in 2010, continues to challenge efforts to stabilize production. Our analysis demonstrated that any global warming with excess of $1.5\text{--}2^\circ\text{C}$ is likely to entail a significant increase in the frequency of heat stress days around flowering and, hence, increase the probability of incurring in conditions that could, ultimately, downturn yield stability. For spring wheat and, to a less extent, for winter wheat as well, this would add to the overall decrease in productivity expected by the mid of the century in the most productive regions in the South of Russia (Belyaeva and Bokusheva, 2018).

Shifts in phenology could taper off, at least partially, the negative impacts of warming, and it has been argued that winter wheat cultivation would benefit more from an anticipated phenology than spring wheat (Rezaei et al., 2015). However, this does not circumvent the problem of a significant higher frequency of heat stress days around flowering in the future, except perhaps under global warming scenarios fulfilling the targets of the Paris Agreement.

Possible pathways for adaptation of crop production to climate change are under consideration worldwide. Often discussed changes are the farm management practices (Azadi et al., 2019; Olmstead and Rhode, 2011), breeding programs for adaptive traits and genes (Reynolds, 2010), crop varietal replacements to heat-tolerant varieties (Atlin et al., 2017; Tanaka et al., 2015), and the expansion of irrigation (Tanaka et al., 2015). Similar strategies have also been suggested as possibilities to adapt Russian agriculture to climate change (Belyaeva and Bokusheva, 2018; Liefert and Liefert, 2015; Morgounov et al., 2018; Paola et al., 2018).

In view of higher yields in winter wheat, Russian grain production would benefit from replacing spring wheat with winter wheat. Historically, winter wheat cultivation was limited to Southern European Russia because of unfavorable conditions in the south of Western Siberia and northern Kazakhstan (late but hot summers, dry autumns, light snow cover during severe winters) (Kirilenko and Dronin, 2011; Kruchkov and Rakovskaya, 1990). In these latter areas, conditions could become more favorable for winter wheat in the future (Belyaeva and Bokusheva, 2018), but likely not to the extent that winter wheat cultivation could become overall profitable.

The consequence of higher temperatures in the future is increased heat availability and improved thermal suitability for wheat cultivation in the north of the Central and Volga regions and the eastern regions of Russia (Belyaeva and Bokusheva, 2018; Paola et al., 2018). This could open opportunities for expanding cultivation areas. Given the projected increase in the frequency of heat stress days around flowering highlighted in our study for these regions, the benefits of such measures could be less than expected if not accompanied by efforts to increase yield stability. In this respect, breeding varieties that are more resistant to heat stress (Ni et al., 2018; Watson, 2019), are expected to assume a very important role. Economic considerations could also curtail the prospect to expand the wheat cropping area northward. To cover the high marginal costs of production, expansion in the grain area would require considerably higher grain prices than currently achievable on the world market, along with investments in the grain infrastructural system (Wegren, 2018).

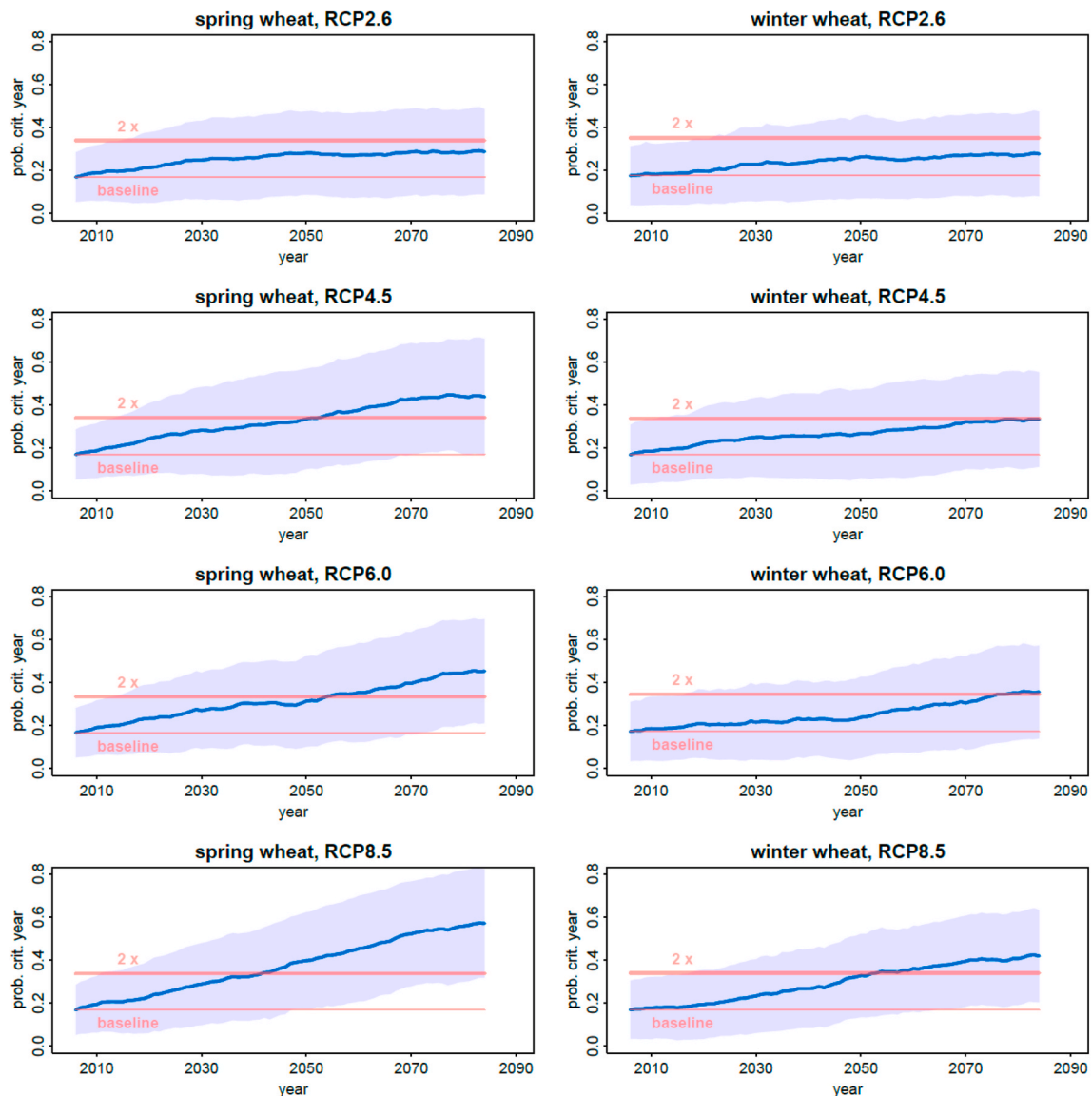


Fig. 4. Probability of incurring in a critical year for sequential 30-years running time windows starting in 1992–2021 and ending in 2070–2099, for spring wheat (left) and for winter wheat (right). Results for RCP 2.6 to RCP 8.5 from top to bottom. The horizontal lines indicate the probability of a critical year for the baseline period 1991–2020 (thin red line) and twice this value (thick red line). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Intensification and re-cultivation of the recently abandoned croplands in Russia could significantly increase wheat production (Schierhorn et al., 2014). However, increasing aridity in such areas may jeopardize the exploitation of the production potential (Dronin and Kirilenko, 2011; Schierhorn et al., 2014).

Earlier studies suggest that the probability of incurring in mega-heatwaves could markedly increase within the next 40 years (Barriopedro et al., 2011). This supports the conclusion from Fig. 4 that without efforts to limit the emissions of greenhouse gases events comparable in impacts to the 2010 heat wave could become rather common in the future.

By no means, we consider our study as being exhaustive. We used climate scenarios representing different future pathways, but there is certainly room for addressing a wider spectrum of projections. Also, our approach to estimate the frequency of heat stress days around flowering relied on using a model of wheat phenology (Olesen et al., 2012) that accommodate adjustments in the heat requirements of spring and winter wheat when temperatures rise. The plausibility of the simulated wheat phenology across the Russian territory was verified in a previous study

(Giannakaki and Calanca, 2019). Yet further work is required to better characterize the distinctiveness of Russian wheat production in relation to wheat varieties and cultivation techniques. Furthermore, future analyses should examine not only heat stress, but also other stress factors that have the potential to harm Russian wheat, including both abiotic (Gate, 1995; Dodd et al., 2011) as well as biotic stress (Todorovska et al., 2009). Finally, we should not forget that wheat could benefit from elevated CO₂ concentrations, both through improved photosynthetic capacity and water-use efficiency (Varga et al., 2015; Webber et al., 2018). Clearly, forthcoming studies should address the implications of elevated CO₂ concentrations for phenology and the occurrence of heat stress in Russian wheat.

Across many areas of the world (United States; Mazdiyasn and AghaKouchak (2015), India: Sharma and Mujumdar (2017), northern China: Li et al. (2019)) there is evidence for droughts and heatwaves to occur at increasing pace as compound events, imposing more-extreme conditions to grain production than either would deliver separately. In Russia, important cultivations areas, such as the Volga Federal District, clearly suffered from the absence of significant precipitation in 2010,

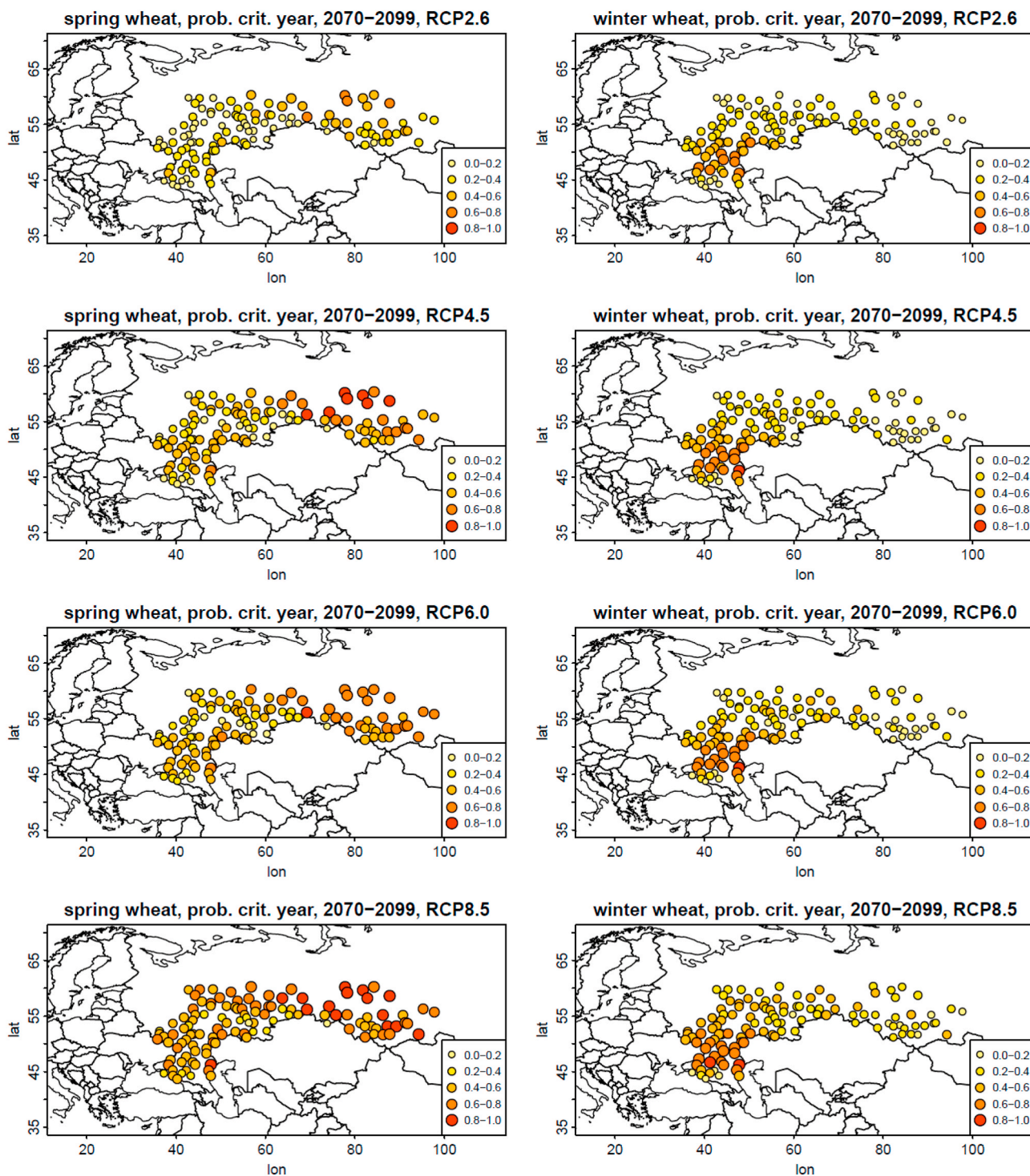


Fig. 5. Probability of incurring in a critical year during 2070–2099, for spring (left) and winter wheat (right). Results for RCP 2.6 to RCP 8.5 are shown from top to bottom. The figure shows averaged results over model chains.

stressing the significance of drought at the local to regional scale for Russian wheat. Yet, for the time being elements pointing to higher drought risks under climate change, for the country as a whole, remain unsubstantiated. According to Frolov et al. (2014) the trend in annual precipitation over 1976–2012 was positive (8 mm per 10 years) across most of the Russian territory. The ISIMIP scenarios also suggest a slight increase in precipitation amounts during the growing season of wheat in the future (not shown).

With this in mind, it is important to tackle interventions aiming at

fulfilling the target of the Paris Agreement with priority, because they would in any case help ensuring Russian wheat yields stability in the mid- and long term. According to recent assessments (Mauritsen and Pincus, 2017; Raftery et al., 2017), the chances that global temperature will rise by less than 1.5 °C, resp. 2 °C are minimal (1%, resp. 5%). The fact that countries responsible for a large share of the global greenhouse gas emissions have resigned from the Paris Agreement makes the Paris targets even harder to achieve. On this background, it becomes even more important for Russia to explore a large palette of options for

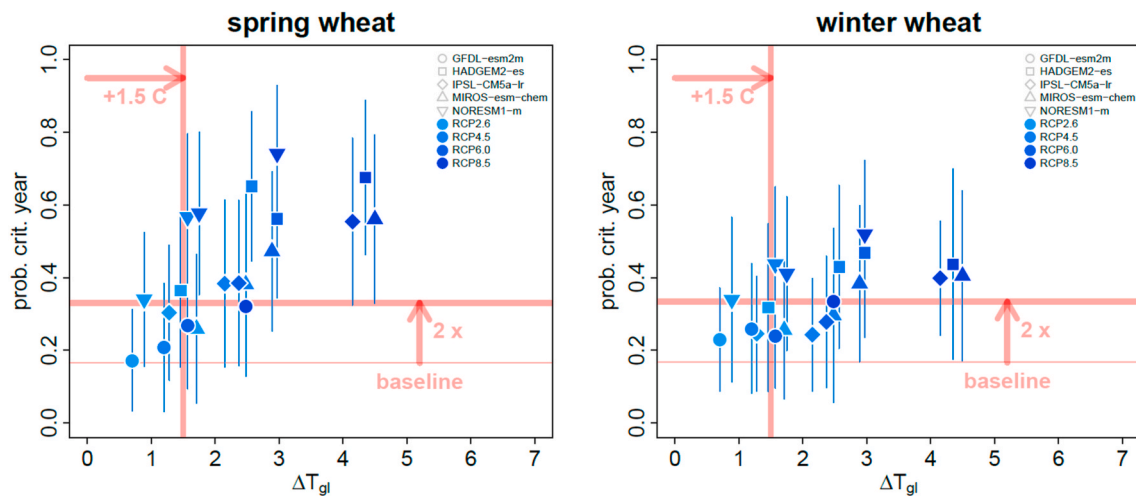


Fig. 6. Probability of incurring in a critical year during 2070-2099 (left: spring wheat, right: winter wheat) as a function of the increase in global mean temperature (ΔT_{gl}) between 1981-2010 and 2070-2099. The vertical line indicates the Paris target ($+1.5^{\circ}\text{C}$), while the red horizontal lines indicate the probability of a critical year during the baseline period and twice this value. For each climate model and RCP, the blue dots represent the mean across sites, whereas the vertical line gives the standard deviation across the sites. Symbols and color intensity as indicated in the legend on the top right of each panel. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

adapting grain production.

5. Conclusions

Current projections indicate that by 2050 the world's population could reach 9.1 billion. Demand for food, in general, and wheat, in particular, is expected to raise accordingly (Godfray et al., 2010). Future food security will not solely depend on average total production, but also on achieving high production stability and price stability on the global grain market. Because of the leading role of Russia on the wheat market, to meet these goals it is imperative to avoid dramatic shortfalls in Russian wheat production. While many factors can contribute to impair wheat development across the Russian territory, heat stress occurring around flowering remain a major challenge. We showed that in 2010 the frequency of heat stress days around flowering was not everywhere exceptionally high. Nevertheless, even so about 40% of the expected grain production was lost in that circumstance.

The heat wave of 2010 (Flach et al., 2018) was the result of the unusual persistence of high pressure systems over the territory of Russia (Dole et al., 2011; Giannakaki and Calanca, 2019). It is still a matter of debate, whether this anomalous situation was mainly of natural origin or came about as a consequence of global warming (Dole et al., 2011; Rahmstorf and Coumou, 2011). Yet, without efforts to limit the emissions of greenhouse gases, events comparable in impacts could become rather common in the future, according to the ISIMIP climate change scenarios. Our results suggest a doubling of the probability of incurring in a critical year by the end of the century already for an increase in global mean temperature of about 1.5°C as compared to today. The probability of incurring in critical years could even increase by a factor of three or more if global mean temperature increases by more than 3.0°C over the coming decades. Adapting wheat varieties and agronomic practices can help reducing the negative impacts of heat stress. Yet, implementation of measures for reducing net greenhouse gas emissions, eventually allowing to fulfill the targets of the Paris Agreement, should nevertheless be tackled with highest priority.

CRedit authorship contribution statement

Barbara Templ: Methodology, Writing - original draft. **Pierluigi Calanca:** Conceptualization, Methodology, Visualization, Writing - review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.wace.2020.100281>.

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