nature climate change

ARTICLES

PUBLISHED ONLINE: 25 MAY 2014 | DOI: 10.1038/NCLIMATE2242

Adverse weather conditions for European wheat production will become more frequent with climate change

Miroslav Trnka[1,2]*, Reimund P. Rötter[3], Margarita Ruiz-Ramos[4], Kurt Christian Kersebaum[5], Jørgen E. Olesen[6], Zdeněk Žalud[1,2] and Mikhail A. Semenov[7]

Europe is the largest producer of wheat, the second most widely grown cereal crop after rice. The increased occurrence and magnitude of adverse and extreme agroclimatic events are considered a major threat for wheat production. We present an analysis that accounts for a range of adverse weather events that might significantly affect wheat yield in Europe. For this purpose we analysed changes in the frequency of the occurrence of 11 adverse weather events. Using climate scenarios based on the most recent ensemble of climate models and greenhouse gases emission estimates, we assessed the probability of single and multiple adverse events occurring within one season. We showed that the occurrence of adverse conditions for 14 sites representing the main European wheat-growing areas might substantially increase by 2060 compared to the present (1981–2010). This is likely to result in more frequent crop failure across Europe. This study provides essential information for developing adaptation strategies.

Recent global warming has markedly shifted the distribution of temperature variability and extremes[1,2] and precipitation patterns[3], although uncertainty remains regarding the relationship between global warming and climatic variability[4]. These shifts have consequences for the production environments of most crops, including wheat, which is globally the second most widely grown cereal crop after rice[5]. A recent study[1] showed that, by 2030, we should expect a twofold increase in the global wheat-growing area threatened by extremely high temperatures during critical developmental stages in a typical year, and a more than threefold increase of the area at risk by 2050. Other studies project[6,7] a significantly higher frequency of extremely unfavourable years under future climate conditions, possibly resulting in poor economic returns in many European regions. This projection is especially true for situations with global warming exceeding 2 °C compared to the pre-industrial era. Although the observed annual temperature (adjusted for short-term variability) so far closely follows the central projections of the Intergovernmental Panel on Climate Change (IPCC; refs 7,8), it should be stressed that several climate projections for the mid-century point far exceed the 2 °C threshold[9].

Wheat production in Europe (Fig. 1), representing 25% of the global wheat area and 29% of global wheat production[10], is affected not only by the frequency of days with high temperatures but also by the occurrence of drought, of late spring frosts and of severe winter frosts associated with inadequate snow cover. In addition, overly wet and/or cool weather enhances disease occurrence, contributes to lodging and complicates crop management. The projected increase in extreme weather events (for example, periods of high temperature and drought) over at least some parts of Europe is projected to increase yield variability[7,11]. Concomitantly, there is evidence of a slowing rate of yield increase, due to multiple factors—mainly the closing of the gap between realized and potential yields[12,13] as well as policies such as stricter environmental regulation[14]. The consequences of shortfalls in European wheat production for global supply (and prices) have been manifested in recent years, including 2007 and 2012[15]. Realizing the critical importance of European growing areas, we aimed to analyse whether and how the various agroclimatic risks for wheat production are likely to develop under long-term climate projections for the period 2051–2070 (subsequently denoted as 2060').

Crop model based analysis[6] has already emphasized the importance of changes in high temperature events relative to drought effects on wheat productivity across a range of European sites. Here, we used a set of agroclimatic indices combined with local-scale climate scenarios based on the most up-to-date CMIP5 (ref. 16) multi-model ensemble and the high-end Representative Concentration Pathway (RCP8.5; ref. 17) to project the adverse condition probability during the wheat-growing season (autumn sowing) in mid-twenty-first-century Europe. We quantified changes for a wide range of adverse conditions, both individually and combined. To our knowledge, this is the first time that multiple stress occurrence risks under climate change have been analysed systematically for an agricultural crop.

Impact on phenology and potential productivity

Simulated dates of sowing, flowering (anthesis) and maturity for the 14 locations were mostly in agreement with the observations from local authorities; however, deviations were found for some locations

[1]Global Change Research Centre, Czech Academy of Sciences, Brno 603 00, Czech Republic, [2]Department of Agrosystems and Bioclimatology, Mendel University in Brno, Brno 603 00, Czech Republic, [3]Plant Production Research, MTT Agrifood Research Finland, FI-50100, Mikkeli, Finland, [4]Research Centre for the Management of Agricultural and Environmental Risks CEIGRAM-AgSystems, Technical University of Madrid, 28040, Spain, [5]Leibniz-Centre for Agricultural Landscape Research, D-15374 Muencheberg, Germany, [6]Aarhus University, Department of Agroecology, BlichersAllé 20, DK-8830 Tjele, Denmark, [7]Computation and Systems Biology Department, Rothamsted Research, Harpenden, Herts, AL5 2JQ, UK. *e-mail: mirek_trnka@yahoo.com

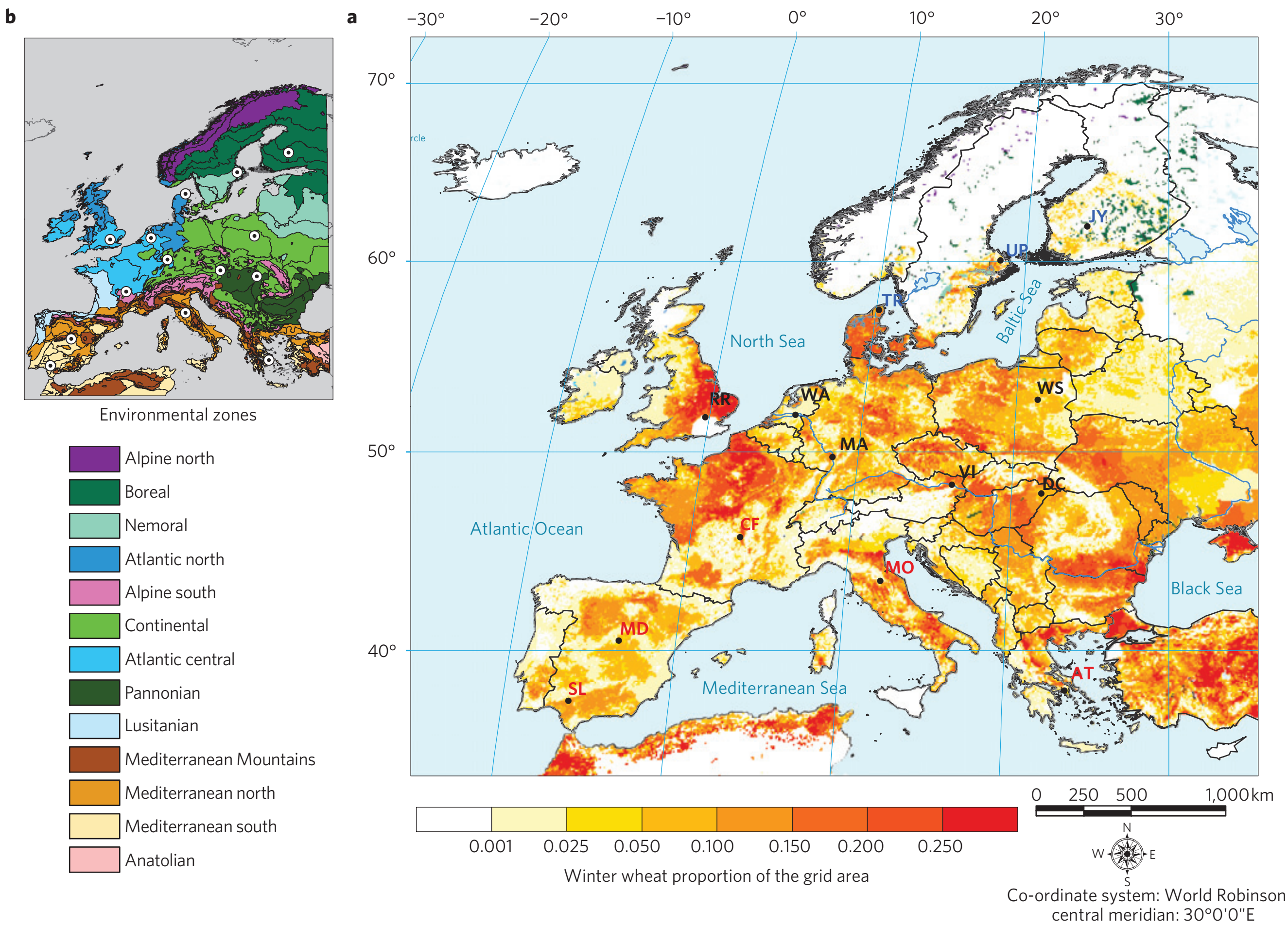

Figure 1 | Overview of the wheat-growing area and environmental zones in Europe. a, Wheat-growing area in Europe based on ref. 30 and the locations of the 14 sites where the frequency of agroclimatic extremes was analysed. Colour coding is used to divide the stations into three groups: north (blue), central (black) and south (red). A more detailed description of the sites is provided in Supplementary Table 1. **b**, Coverage of the main environmental zones in Europe[25] by the 14 selected sites.

(especially the somewhat late estimated dates for Madrid (MD)) as a consequence of using the same parameterization for all of Europe. Figure 2a shows sowing dates being moved forward on average by 15 ± 7 days in 2060 compared to the present. Simulations showed that the anthesis and maturity dates were two weeks earlier across all sites (Fig. 2b,c). This advancement was linked to enhanced crop development rates with higher temperatures (Fig. 2d). Figure 2e shows that the site potential productivity indicator (effective global radiation considering suitable temperatures and soil water content, as defined in the Methods and the Supplementary Information) is expected to increase slightly at northern sites from sowing to anthesis, whereas southern sites mostly show declines. This decrease was caused by the vegetative period shortening from sowing to anthesis, the shift of this period towards shorter day lengths (that is, more towards the winter months) and the increased drought incidence at some sites. The results for anthesis to maturity (Fig. 2f) mostly showed a decrease in the effective global radiation. At 13 out of 14 sites, the results of more than half of the CMIP5-based climate model runs showed decreasing effective global radiation, thus reducing the potential for plant biomass accumulation and for crop yields.

Probability of individual adverse event occurrence

The risk of a severe frost event in the absence of snow cover increased at the two most northern sites but was lower or unchanged at all of the remaining sites (Fig. 3a). In the case of late spring frost risk, we noted a decrease at one site, whereas increases were likely at six other sites (Fig. 3b). An excessive wet period with the possibility of water logging between sowing and anthesis was becoming increasingly likely at three sites in the UK, the Netherlands and Denmark (Fig. 3c), with little or no change at the other sites. The frequency of heavy precipitation events that are considered precursors of severe lodging was more likely to decrease than increase at seven sites, mostly in central and southern regions. There was only one site where the risk increased according to most scenarios (Fig. 3d). Fewer than one third of the sites showed an increased chance of unusually dry conditions during the entire growing season (Fig. 3e), with three southern sites being most affected. The drought risk in the period from sowing to anthesis was more likely to increase than decrease at four sites (three of them in the south), whereas the remaining sites showed no or very small changes (Fig. 3f). The likely increase of a severe drought event after anthesis affected only the southern locations along the western Mediterranean (Fig. 3g). The heat stress risk at anthesis, which would affect floret fertility, is likely to increase at ten sites (Fig. 3h), with northern sites being those least affected. Heat stress during grain filling is more likely to increase at six sites (most markedly in the southern sites), with another three sites showing a slightly increased risk according to some scenarios from the CMIP5 ensemble (Fig. 3i).

The probability of adverse conditions during sowing was shown to be more likely to increase than decrease at seven sites (Fig. 3j).

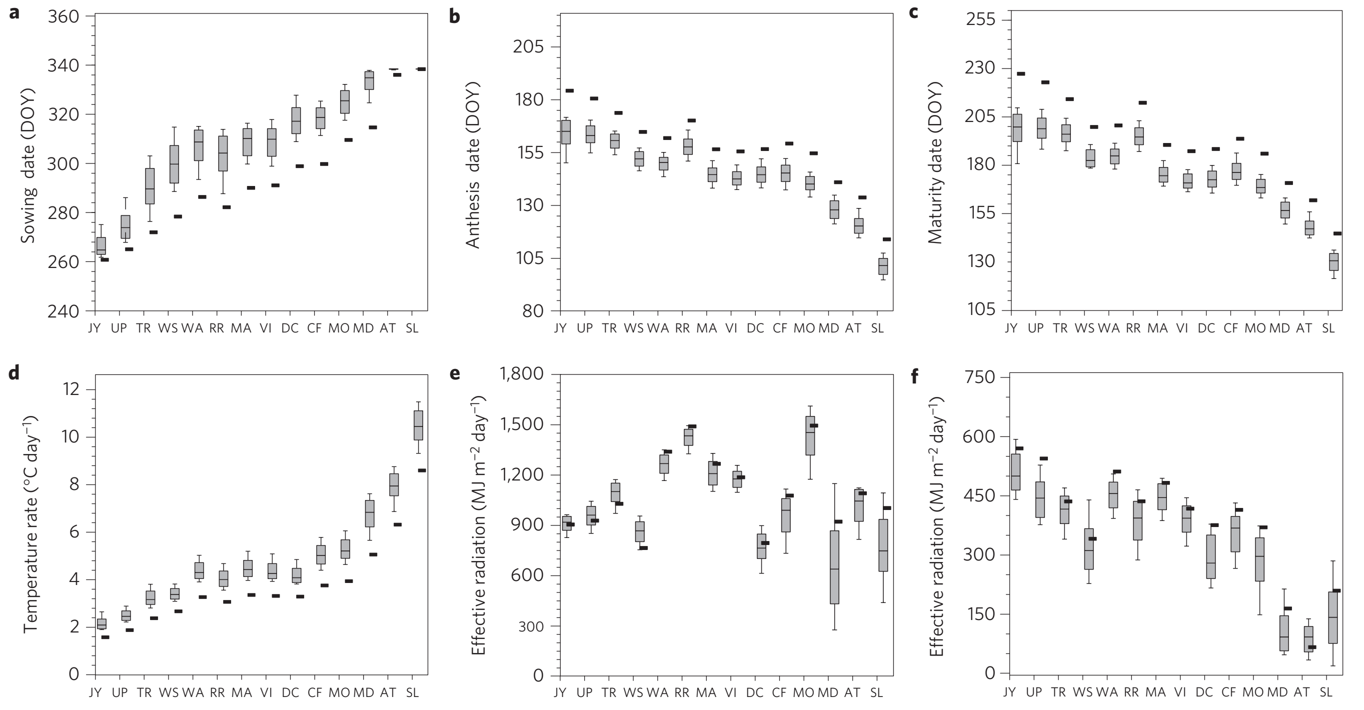

Figure 2 | Dates of key phenological stages and values of agroclimatic indicators for baseline and projected climate conditions. a, Sowing date. **b**, Anthesis date. **c**, Maturity date. **d**, Temperature rate during sowing to maturity. **e**, Effective global radiation from sowing to anthesis. **f**, Effective global radiation from anthesis to maturity. Black rectangles indicate the 1981–2010 baseline and box plots indicate the 2060 (RCP8.5) climate scenarios. The locations are ordered from north to south along the *x* axis. DOY represents day of year.

This risk of deteriorating conditions for sowing was pronounced for all of the northern sites and two western sites (WA and RR). However, the suitability for harvesting seemed much less likely to be a problem (Fig. 3k), with at least two sites showing an improvement in harvesting conditions. This improvement was partly a consequence of the date of maturity advancement.

Probability of multiple adverse event occurrence

Although the reported increase in the individual frequency of adverse events is worrisome, the most unsettling possibility is illustrated by the combined probability of having at least one of 11 indicators crossing the defined threshold during one season (Fig. 3l). Under the projected climate for 2060, the agroclimatic extremes probability was likely to increase at all of the sites for all of the wheat cultivar types, with the exception of CF for early cultivars (Fig. 4a–c). Whereas for all of the sites on average, the risk of at least one adverse event was likely to increase by 30%, at some sites (UP, RR, MA, VI and SL) the risk was likely to double. Using a medium-duration cultivar (Fig. 4b) as a reference, the mean probability of a single adverse event occurring per season was found to be 11.2% under the baseline and 20.7% in 2060 (according to RCP8.5). Furthermore, the probability of two adverse events occurring for a medium-type cultivar in any given season (Fig. 4e) was shown to be likely to increase at 11 out of 14 sites. Considering the lowest impact that was projected from the global climate model (GCM) ensemble for each site, only a slight reduction in the probability (9.7% compared to 11.2%) of adverse events may be expected. However, the realization of the most severe case from the GCM ensemble would result in a more than threefold increase in the adverse event probability. The mean likelihood of two adverse events per season was 1.7% under the baseline but more than twice that (4.0%) under the projected climate change, with the lowest GCM mean value being 0.9% (Fig. 4e). The likelihood of two events per season considering the highest GCM value at each site increased more than sixfold (to 10.4%) compared to the baseline. Furthermore, the probability of three adverse events occurring within a location during one season was evaluated, recognizing that three events per season would represent an exceptional season. Such extreme cases were found under the baseline conditions only at the DC, MD and SL sites, and even then very rarely (less than once per 125 years), whereas under the projected future climatic conditions only three sites (TR, RR and VI) show no risk of such a season. The mean return period for three adverse events occurring in 2060 was projected to be between 20 and 30 years at Spanish sites and between 75 and 250 years at the remaining sites.

Excluding adverse conditions for sowing and harvest did not affect the overall results of the analysis. Obviously, the probability of any given season being affected by adverse conditions (when the sowing and harvest conditions were not considered) decreased, but the overall effect on the number of sites that were negatively affected under the future climate remained almost unchanged.

Effect of crop timing and soil conditions

Exposure to several of the adverse events depends on the timing of anthesis and maturity, which was influenced by the cultivar type used (Fig. 4). Whereas the cultivar type did not influence the number of sites facing a higher probability of at least one event per season (Fig. 4a–c), it had a marked effect on the chances of at least two adverse events (Fig. 4d–f). The probability of at least one adverse event per season increased at most of the sites, especially for the late cultivar (Fig. 4c). Because we were concerned about potentially overestimating the frequency of adverse and extreme events occurring owing to the longer-than-observed phenological development in the more southern sites, we altered the photoperiod sensitivity. This alteration led to a decrease in the adverse event exposure, especially at southern and some central European locations (Supplementary Fig. 2), but their increased frequency was still considerable. It should also be noted that one of the main adaptations to climatic warming in many areas of Europe would be switching to cultivars with a longer growth

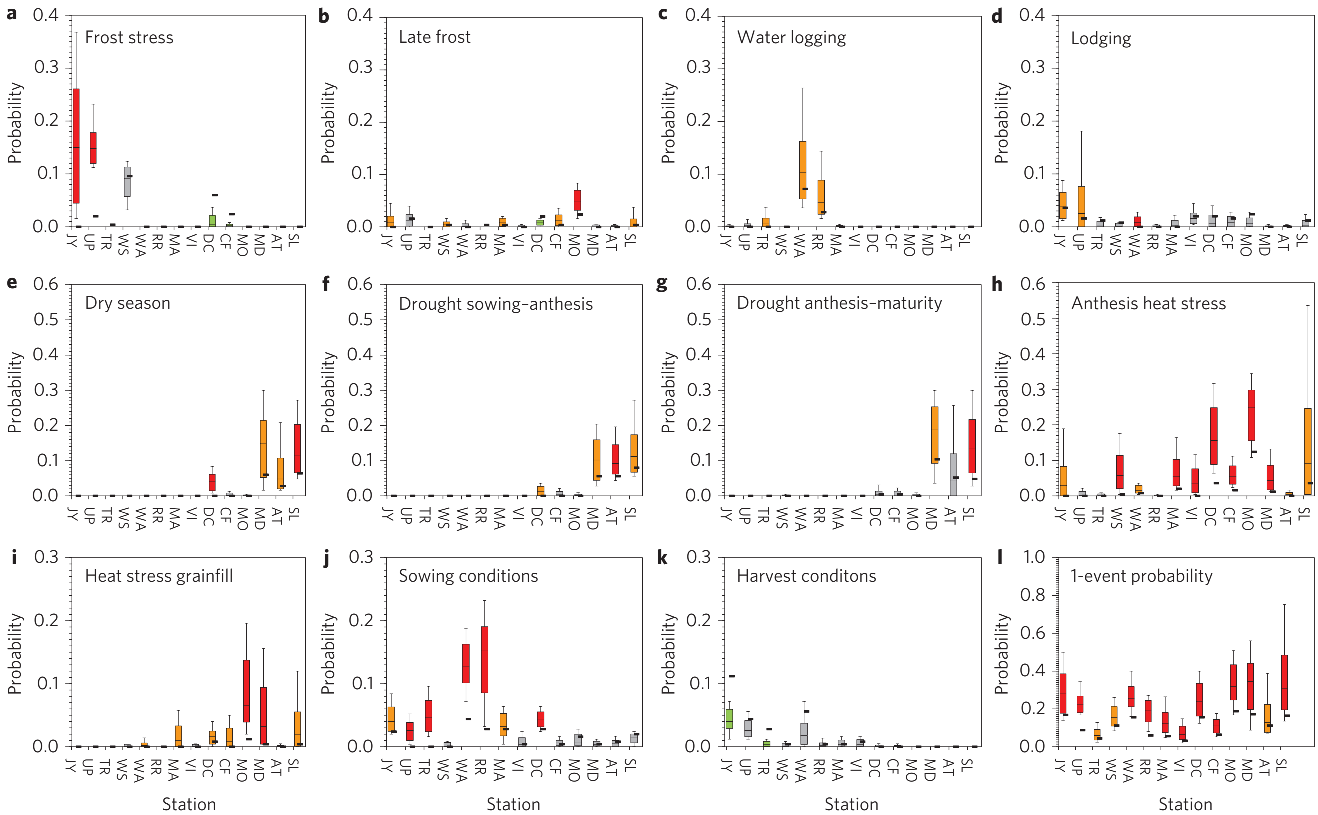

Figure 3 | Probability of the occurrence of adverse agroclimatic conditions under baseline and projected climate. a, Severe winter frost without snow cover. **b**, Late frost. **c**, Excessive soil moisture with water logging from sowing to anthesis. **d**, High precipitation event with the possibility of widespread lodging. **e**, Severely dry growing season (sowing–maturity). **f**, Severe drought event between sowing and anthesis. **g**, Severe drought event between anthesis and maturity. **h**, Heat stress at anthesis. **i**, Heat stress during grain filling. **j**, Adverse conditions during sowing. **k**, Adverse conditions during harvest. **l**, At least one extreme event of the type **a**–**k** during the period from sowing to maturity. Black rectangles indicate the 1981–2010 baseline and box plots indicate the 2060 (RCP8.5) climate scenarios. The calculations consider a medium-ripening cultivar. The locations are ordered from north to south along the *x* axis. The red boxes mark the sites where the results for at least 14 out of the 16 CMIP5 models showed an increased probability of adverse events compared to the baseline. The orange boxes mark the sites where more than half of the CMIP5 models showed an increased probability of the adverse event. The green boxes mark the sites where results for all of the CMIP5 models showed a decreased probability of extreme events. The grey boxes mark all of the other cases.

duration[17], which may increase exposure to adverse weather events. Our results demonstrate that the risk of a season being affected negatively by adverse conditions depends on the changes in the occurrence probabilities of such events, on the potential exposure length and on the sensitive period timing. For example, in cases of late cultivars, for which anthesis and maturity occur later in the year, the chance of heat and drought stresses increases.

Soil conditions play an important role in the course and severity of some adverse events, especially those affected by lack or excess of soil water. Supplementary Fig. 3 shows that light soils (with maximum water content in the rooting zone available to plants at 150 mm) would face higher mean frequency of the adverse event occurrence under baseline and future climates than medium soil (available water content at 270 mm). The effect was more pronounced on the southern sites and for the late-maturing cultivar. It is interesting to note that the relative increase of the adverse event probability under future climate compared to baseline was smaller on light soils, mainly owing to the fact that the probability of such events under the baseline climate was already high.

Consequences for potential adaptation strategies

An adaptation option that might be pursued based on the results we presented (Fig. 4) is a focus on early-ripening cultivars seeking 'stress avoidance'. Although it seems that this strategy would allow for a significant decrease in the adverse condition risk at most of the sites, it comes at a price (see, also, ref. 18). Supplementary Fig. 1 clearly indicates that shortening the growing season reduced the effective global radiation, thus probably decreasing yield potential. The pros and cons of the benefits and risks of such a strategy are further highlighted in Table 1 (the locations are ordered from north to south). This illustrates the trade-offs of using early or late cultivars instead of a medium cultivar. Switching to an earlier cultivar reduced the exposure to extreme events and shifted the time of anthesis to a period with less heat and drought stresses (in some cases alleviating other stresses as well). At most sites, and especially in the southernmost locations, the effect of such a cultivar shift was substantial, and using earlier cultivars led to greatly reduced risks. The results imply that there is a greater scope for introducing earlier cultivars than was tested here. However, Supplementary Fig. 1 also documents that under most scenarios and at all sites, the effective global radiation that we used as the indicator of potential productivity (more details in Methods and Supplementary Information) decreased, and that this decrease could be worsened by switching to earlier cultivars, especially at southern sites.

Using later-maturing cultivars had the opposite effect and led to an increased probability of adverse events, especially in the central and southern sites. When using the relative increase of the adverse event probability as an indicator, it was clear that using a late cultivar would be a risky adaptation strategy, as the likelihood

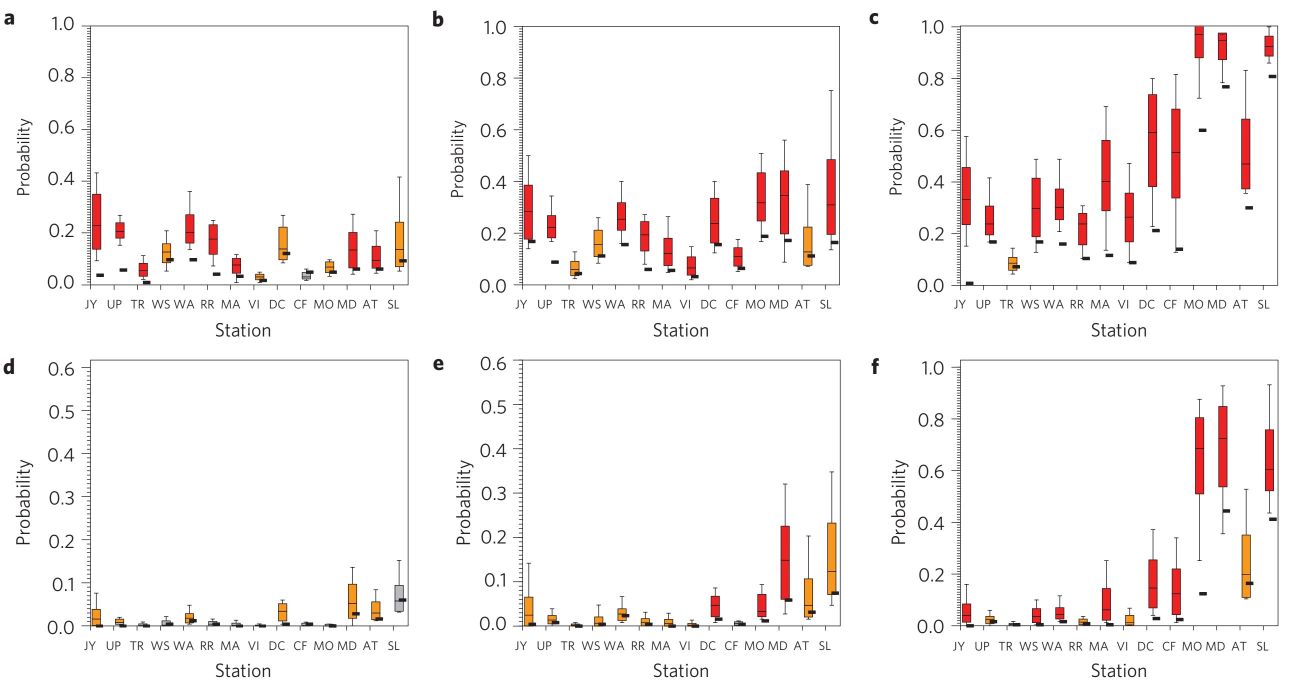

Figure 4 | Effect of the selected cultivar type on the probability of occurrence of adverse events from sowing to maturity. a–c, Probability of occurrence of at least one adverse event. **d–f**, Probability of occurrence of two adverse events. **a**,**d**, Represent an early-maturing cultivar. **b**,**e**, Represent a medium-maturing cultivar. **c**,**f**, Represent a late-maturing cultivar. The colour coding follows that of Fig. 3.

Table 1 | The benefits/risks of using early/medium/late wheat cultivars for the 2060 (RCP8.5) scenario expressed as a change in the probability of at least one adverse weather event per season and effective global radiation from the baseline (1981–2010) values of a medium cultivar.

Site	Acronym	Absolute change in the 1-event probability with the change of the cultivar type compared with baseline			Relative change in the 1-event probability following the change of the cultivar type compared with baseline			Relative change of the effective global radiation following the change of the cultivar type		
		Early	Medium	Late	Early	Medium	Late	Early	Medium	Late
Jyvaskyla	JY	0.08	0.11	0.18	0.45	0.68	1.06	−0.15	−0.03	0.02
Uppsala	UP	0.12	0.14	0.16	1.38	1.56	1.86	−0.18	−0.03	0.08
Tylstrup	TR	0.01	0.02	0.04	0.30	0.44	0.90	−0.18	−0.04	0.07
Warsaw	WS	0.01	0.05	0.19	0.08	0.43	1.69	−0.25	−0.09	0.01
Wageningen	WA	0.06	0.11	0.16	0.38	0.70	1.01	−0.23	−0.07	0.03
Rothamsted	RR	0.11	0.13	0.16	1.90	2.14	2.63	−0.26	−0.08	0.04
Mannheim	MA	0.02	0.07	0.37	0.29	1.28	6.58	−0.18	−0.06	−0.01
Vienna	VI	0.00	0.04	0.23	−0.09	1.29	7.21	−0.21	−0.07	−0.01
Debrecen	DC	0.00	0.09	0.40	0.02	0.59	2.59	−0.23	−0.13	−0.06
Clermont-Ferrand	CF	−0.03	0.04	0.45	−0.46	0.70	6.97	−0.21	−0.12	−0.08
Montagnano	MO	−0.12	0.15	0.76	−0.64	0.81	4.03	−0.28	−0.27	−0.33
Madrid	MD	−0.04	0.15	0.77	−0.23	0.86	4.48	−0.20	−0.13	−0.19
Athens	AT	−0.01	0.04	0.40	−0.06	0.34	3.54	−0.27	−0.27	−0.32
Seville	SL	−0.01	0.18	0.76	−0.05	1.07	4.64	1.87	0.27	−0.57

Green colour bars stand for favourable changes and red colour bars stand for unfavourable changes; the bar length indicates the magnitude of the change. The values for the medium cultivar represent a change in the 1-event probability or effective global radiation between the baseline and 2060 (RCP8.5) scenarios. The values for the early and late cultivars represent the cumulative change that is caused by a change in the climate and cultivar. The change in the effective global radiation covers the period from sowing to maturity.

of adverse event exposure greatly increases. However, according to Supplementary Fig. 1, the use of late-maturing cultivars also improved levels of effective global radiation. At northern sites, late-cultivar use could almost ameliorate the decrease in the effective global radiation index without the penalty of increased exposure to adverse agroclimatic conditions. In central Europe, switching to late-maturing cultivars considerably increased the adverse event frequency, and late-maturing cultivar use seemed not to be an option for southern sites.

These findings highlight that the adaptation strategies must be a compromise between using early-ripening cultivars to provide 'stress avoidance' and maintaining a growing season length with the highest possible effective global radiation to sustain current yields or minimize yield decrease.

Our results further show the urgent need to consider multiple adverse events in impact analyses. For example, for sites where the increase of high-temperature stress events at anthesis is accompanied by increased drought stress, improved water management and/or supplementary irrigation might partially relieve both stresses.

Discussion and conclusions

Previous studies assessing agricultural impacts have demonstrated that the effects depend on the crop, cropping season and region within Europe[19], but few studies have considered the cropping system responses to changes in the frequency and severity of climatic extremes (see, for example, ref. 20 for the Iberian Peninsula). However, it is well known that the impacts of such extreme events can be substantial[5]. Previous studies have emphasized the possibility of considerable northward expansion of the thermal suitability of crop production in Europe (indirectly suggesting major shifts in the location of agriculture production) without fully considering changes in the risk of adverse events[19,21]. Our results show that, despite large uncertainty in climate projections within the CMIP5 ensemble, the overall adverse event frequency is much more likely to increase than decrease, which is the case for all of the sites in the analysed European domain.

From the standpoint of production stability, it is encouraging that some central (WS and VI) and north-western European (WA, MA and TR) growing areas are likely to face comparatively small increases in adverse event occurrence. Nevertheless, the fact that the majority of the sites show a greatly increased probability of single adverse events suggests, in turn, that risk of crop failure would increase across large portions of the European wheat-cropping area. Such a development would have profound repercussions given the importance of European wheat production in the global food trade. Moreover, more frequent adverse conditions for wheat at any particular location would probably be accompanied by yield reductions in other crops (both cereals and non-cereals), as their growing seasons and sensitive periods at least partly overlap. We stressed that the results are valid for wheat that is grown on free-draining soils with the ability to hold a significant amount of water available to plants. The severity and frequency of some of the adverse events (for example, drought stress or water logging) could be different on sandy or heavy clay soils.

Our results highlight the potential of adverse impacts of a changing climate on wheat and show that the associated potential adaptations to these impacts should consider adverse and extreme weather event effects in a more comprehensive way than is usually done in impact assessments based on crop models, which very often do not include such event effects[22]. Moreover, focusing on single adverse events may lead to an incomplete risk perception. Impact severity will depend on the cultivar characteristics and, obviously, on the spatial and temporal climate change patterns. This dependence calls for a regionalization of adaptation strategies: whereas for some regions it is important to breed cultivars that are capable of coping with an increased frequency and magnitude of heat stress around flowering, in some regions it will be equally important to maintain tolerance of low temperatures. In other regions, research should focus on water logging, lodging or field accessibility. Therefore, national and EU research and agricultural policies should encourage and promote response diversity of wheat varieties[23], which would enhance climate resilience by enabling the crop to cope with different region- and season-specific threats, rather than focusing on one or two particular issues.

Methods

The simulation of adverse weather events for wheat was performed for 14 European sites (Supplementary Table 1 and Fig. 1) that were mostly located in lowland areas, and the study domain covered the area between 5.9° W–25.7° E and 37.4° N–62.4° N. Thirteen European countries are represented in the database, covering the current major wheat-producing regions of the EU (Fig. 1a) as well as areas where wheat might be grown in the future[24]. Environmental zones[25] with the highest proportion of arable land were included (Fig. 1b). For each site and each GCM from the CMIP5 ensemble[16] (in total, 16 GCMs were used—see Supplementary Table 2), we generated 300 years of daily weather series, representing the baseline scenario corresponding to 1981–2010, and 300 years for the future climate scenario corresponding to 2051–2070 for RCP8.5 (Supplementary Methods), which was denoted as 2060 (RCP8.5). Both the baseline and future climate scenarios were generated by the LARS-WG 5.5 weather generator[26]; in each run, the first 50 years were used to initiate the calculation, and only the results from the remaining 250 years of data were retained for the subsequent analyses. For each site, we used three types of cultivars according to the maturity date and two levels of photoperiod sensitivity (Supplementary Tables 1 and 3). The mean sowing, anthesis and maturity dates for the baseline conditions (Supplementary Table 1) were estimated using the AgriClim software[27]. It is assumed that these cultivars represent winter wheat in all locations, except for SL and AT where current temperatures constrain vernalization. The simulated cultivars represent spring wheat in these locations, currently sown there in both autumn and winter. Autumn sowing was chosen to keep the sowing within the same season for all locations and make comparison among them easier.

The duration of phenological phases was calculated according to Olesen *et al.*[17] using accumulated degree days (°Cd) above the base temperature combined with the day-length response for the period from emergence to anthesis. It was assumed that these cultivars represent winter wheat in all locations but in SL and AT, which present constraints to the vernalization requirements. The simulated cultivars represented spring wheat in these locations, currently sown there in both autumn and winter. Autumn sowing was chosen to keep the sowing within the same season for all locations and allow comparison among them. The sowing dates were determined automatically as the first day after the mean air temperature dropped below 13 °C for more than five subsequent days with the soil moisture above one third of its relative water-holding capacity. When calculating evapotranspiration, an adjustment for the atmospheric CO_2 concentration was made by reducing the reference evapotranspiration by a scaling factor[28]. The value of the scaling factor for 2060 was estimated to be 0.94 of the baseline values. We used one soil profile for all of the sites, with homogeneous soil properties assumed throughout the top and subsoil layers to enable comparison among sites. The plant-available water at field capacity in the top 0.1 m of the soil was assumed to be 20 mm, with 83 mm being stored in the topsoil (up to a depth of 0.4 m) and 270 mm in the entire profile (a depth of 1.3 m). We used a single free-draining soil with good water-holding properties and a relatively deep profile, allowing us to easily perform between-site comparisons of the climate signal.

To describe the major adverse conditions for wheat production, we used the set of 11 indicators that is described in Supplementary Table 4 to cover the major causes of low yields of wheat across Europe. The final set of indicators was required not only to represent conditions negatively affecting growth but also to hamper the ability to sow and harvest the crop at the optimal time. The selection of factors negatively affecting crop yield relied on the analysis of ref. 29 and included the following: indicators of frost damage, water logging, lodging, heat stress, drought stress and adverse conditions during sowing and harvest. The indicator formulation and its rationale are described in detail in the Supplementary Methods. Although the 11 indices focused on the agroclimatic extremes (adverse conditions), we also calculated the sum of the effective global radiation[27]. This indicator provides a measure of the potential productivity and represents the sum of global radiation of days with a daily mean air temperature above 5 °C, daily minimum air temperature above 0 °C, no snow cover and actual to reference evapotranspiration ratio above 0.4.

Received 8 November 2013; accepted 8 April 2014; published online 25 May 2014

References

1. Gourdji, S. M., Sibley, A. M. & Lobell, D. B. Global crop exposure to critical high temperatures in the reproductive period: Historical trends and future projections. *Environ. Res. Lett.* **8,** 024041 (2013).
2. Rahmstorf, S. & Coumou, D. Increase of extreme events in a warming World. *Proc. Natl Acad. Sci. USA* **108,** 17905–17909 (2011).
3. Chunlei, L. & Richard, P. A. Observed and simulated precipitation responses in wet and dry regions 1850–2100. *Environ. Res. Lett.* **8,** 034002 (2013).
4. Huntingford, C., Jones, P. D., Livina, V. N., Lenton, T. M. & Cox, P. M. No increase in global temperature variability despite changing regional patterns. *Nature* **500,** 327–330 (2013).
5. Reyer, C. P. O. *et al.* A plant's perspective of extremes: Terrestrial plant responses to changing climatic variability. *Glob. Change Biol.* **19,** 75–89 (2013).
6. Semenov, M. A. & Shewry, P. R. Modelling predicts that heat stress, not drought, will increase vulnerability of wheat in Europe. *Sci. Rep.* **1,** 66 (2011).
7. IPCC, *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* (Cambridge Univ. Press, 2012).
8. Rahmstorf, S., Foster, G. & Cazenave, A. Comparing climate projections to observations up to 2011. *Environ. Res. Lett.* **7,** 044035 (2012).
9. Joshi, M., Hawkins, E., Sutton, R., Lowe, J. & Frame, D. Projections of when temperature change will exceed 2 °C above pre-industrial levels. *Nature Clim. Change* **1,** 407–412 (2011).
10. FAOSTAT. Available from: http://faostat.fao.org/site/567/default.aspx#ancor (2012) (cited 20 October 2013).

11. Porter, J. R. & Semenov, M. A. Crop responses to climatic variation. *Phil. Trans. R. Soc. Lond. B Biol. Sci.* **360,** 2021–2035 (2005).
12. Ewert, F., Rounsevell, M. D. A., Reginster, I., Metzger, M. J. & Leemans, R. Future scenarios of European agricultural land use: I Estimating changes in crop productivity. *Agr. Ecosyst. Environ.* **107,** 101–116 (2005).
13. Lobell, D. B., Cassman, K. G. & Field, C. B. Crop yield gaps: Their importance, magnitudes, and causes. *Annu. Rev. Env. Resour.* **34,** 179–204 (2009).
14. Brisson, N. *et al.* Why are wheat yields stagnating in Europe? A comprehensive data analysis for France. *Field Crop Res.* **119,** 201–212 (2010).
15. Mitchel, D. *A Note On Rising Food Prices* (The World Bank, 2008).
16. Taylor, K. E., Stouffer, R. J. & Meehl , G. A. An overview of CMIP5 and the experiment design. *Bull. Am. Meteor. Soc.* **93,** 485–498 (2012).
17. Olesen, J. E. *et al.* Changes in time of sowing, flowering and maturity of cereals in Europe under climate change. *Food Addit. Contam. Part A Chem. Anal. Control. Expo. Risk Assess.* **29,** 1527–1542 (2012).
18. Rötter, R. P. *et al.* Modelling shifts in agroclimate and crop cultivar response under climate change. *Ecol. Evol.* **3,** 4197–4214 (2013).
19. Olesen, J. E. *et al.* Uncertainties in projected impacts of climate change on European agriculture and terrestrial ecosystems based on scenarios from regional climate models. *Climatic Change* **81,** 123–143 (2007).
20. Ruiz-Ramos, M., Sánchez, E., Gallardo, C. & Mínguez, M. I. Impacts of projected maximum temperature extremes for C21 by an ensemble of regional climate models on cereal cropping systems in the Iberian Peninsula. *Nat. Hazards Earth Syst. Sci.* **11,** 3275–3291 (2011).
21. Fischer, G., van Velthhuizen, H. T., Shah , M. M. & Nachtergaele, F. O. *Global Agroecological Assessment for Agriculture in 21st Century; Methodol. Results* (IIASA, 2002).
22. Rötter, R. P., Carter, T. R., Olesen, J. E. & Porter, J. R. Crop–climate models need an overhaul. *Nature Clim. Change* **1,** 175–177 (2011).
23. Kahiluoto, H. *et al.* Cultivating resilience by empirically revealing response diversity. *Glob. Environ. Change* **25,** 186–193 (2014).
24. Elsgaard, L. *et al.* Shifts in comparative advantages for maize, oat and wheat cropping under climate change in Europe. *Food Addit. Contam. Part A Chem. Anal. Control. Expo. Risk Assess.* **29,** 1514–1526 (2012).
25. Metzger, M. J., Bunce, R. G. H., Jongman, R. H. G., Mücher, C. A. & Watkins, J. W. A climatic stratification of the environment of Europe. *Glob. Ecol. Biogeogr.* **14,** 549–563 (2005).
26. Semenov, M. A., Donatelli, M., Stratonovitch, P., Chatzidaki, E. & Baruth, B. ELPIS: A dataset of local-scale daily climate scenarios for Europe. *Clim. Res.* **44,** 3–15 (2010).
27. Trnka, M. *et al.* Agroclimatic conditions in Europe under climate change. *Glob. Change Biol.* **17,** 2298–2318 (2011).
28. Kruijt, B., Witte, J-P. M., Jacobs, C. M. J. & Kroon, T. Effects of rising atmospheric CO_2 on evapotranspiration and soil moisture: A practical approach for the Netherlands. *J. Hydrol.* **349,** 257–267 (2008).
29. Olesen, J. E. *et al.* Impacts and adaptation of European crop production systems to climate change. *Eur. J. Agron.* **34,** 96–112 (2011).
30. Monfreda, C., Ramankutty, N. & Foley, J. A. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Glob. Biogeochem. Cycle* **22,** GB1022 (2008).

Acknowledgements

Support from J. Balek (programming and data handling) and D. Semerádová (preparation of Fig. 1) is greatly appreciated. This study was performed thanks to the support of the FACCE-JPI knowledge hub and project MACSUR. The contributions of M.T and Z.Z were funded through a project of the National Agency for Agricultural Research (project 'Crop modelling as a tool for increasing the production potential and food security of the Czech Republic under Climate Change' no. QJ1310123) and the 'Establishment of International Scientific Team Focused on Drought Research' (no. OP VK CZ.1.07/2.3.00/20.0248). R.P.R. was funded by the Academy of Finland's NORFASYS project (decision no. 268277). M.R-R. was funded by the Ministry of Economy and Competitiveness (MULCLIVAR project CGL2012-38923-C02-02). Rothamsted Research receives grant-aided support from the Biotechnology and Biological Sciences Research Council of the UK. We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modelling groups (listed in Supplementary Table 2) for making available their model output.

Author contributions

M.T., M.A.S. and R.P.R. conceived and planned the study; M.T. and Z.Z. led the AgriClim software development; M.T., M.R-R., R.P.R., J.E.O. and K.C.K. performed the parameterization of the software; M.T. performed the calculation and initial analysis; M.A.S. was responsible for development of climate change scenarios and weather data. All the authors jointly developed the final set of indices and contributed to writing the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to M.T.

Competing financial interests

The authors declare no competing financial interests.