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Global loss of climatically suitable areas for durum wheat growth in the future

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Abstract

Durum wheat (*Triticum durum* Desf.) is a minor cereal crop of key importance for making pasta, couscous, burghul, puddings, bread and many other traditional foods, due to its physical and chemical characteristics. The global demand for high-quality food made of durum wheat has been increasing, which poses a challenge in the face of climate change. Major share of durum wheat production is currently located in semi-arid climates, where the risk of climate extremes such as drought and heat stress will likely substantially increase in the future. To provide a first estimate of future global arable land climatically suitable for growing durum wheat, we develop a suitability model based on support vector machines. The current total share of global arable land climatically suitable to grow rainfed durum wheat is around 13%. Climate change may decrease the suitable area by 19% at mid-century and by 48% at the end of the century. Widespread loss of suitable areas is foreseen in the Mediterranean regions and northern America. On the other hand, climate may become suitable to grow durum wheat in many regions of central and western Europe, while the largest gain in suitability is estimated in some parts of Russia. The overall net loss of suitable areas requires the development and the future adoption of effective and sustainable strategies to stabilize production and adapt the entire food supply chain. Our study also clearly demonstrates the importance of limiting global warming to levels well below 2 °C at the end of the century, which would substantially limit the loss of climatically suitable areas.

1. Introduction

Durum wheat currently represents around 8% of the total wheat crop production, with the main cultivation regions being concentrated in few suitable areas such as the Mediterranean Basin, the North American Great Plains, Russia and Kazakhstan (Tidiane Sall *et al* 2020, Zampieri *et al* 2020). In these areas, durum wheat is a main staple crop and an important commodity (Rharrabti *et al* 2001, Royo *et al* 2014, Asseng *et al* 2018). Compared to bread (or common) wheat (*Triticum aestivum* L.), the largest cultivated wheat species, durum wheat is characterized by stronger gluten, grain yellow color, lower glycemic index and longer durability, which are all essential properties to make pasta (Nazco *et al* 2014).

Global distribution of durum wheat production areas has been, since its origin around 10 000 years ago (Soriano *et al* 2018), shaped by various factors, including its sensitivity to climate, soil-borne diseases, micronutrient imbalances as well as human migrations and demand-side (Baloch *et al* 2017). Countries in the margins of the Mediterranean Basin, where the diet habits have traditionally strongly relied on durum wheat, currently produce nearly 75% of global durum wheat, while being at the same time also the biggest importers (Xynias *et al* 2020).

How much climate change will affect the production and the quality of durum wheat is an overarching question. The global Mediterranean-like climates where durum wheat is grown are hot-spots of climate change, where temperature is warming faster than in other world regions (Diffenbaugh and Giorgi 2012) and changes in precipitation regimes and extremes will pose a threat for societies and ecosystems (Polade *et al* 2017, Cramer *et al* 2018, Brogli *et al* 2019), compromising, for instance, the resilience of natural ecosystems and agriculture. Durum wheat production is sensitive to heat stress and drought (Fontana *et al* 2015, Guzmán *et al* 2016) which are projected to increase in durum wheat suitable areas (Dosio *et al* 2018, Naumann *et al* 2018). These issues can reduce the stability of durum wheat yields, especially if no adaptation measures are taken (Dettori *et al* 2017, Dixit *et al* 2018; Zampieri *et al* 2020).

Ultimately, climate change could also result in completely unsuitable areas for durum wheat cultivation, as it has been already anticipated for the 'Fertile Crescent' in the Middle East, where wheat was domesticated (Kitoh *et al* 2008, Preece *et al* 2017). Thus, a socio-economic urgent question arises on whether durum wheat cultivation will still be profitable and sustainable under future climate conditions despite efforts in optimizing and adapting agro-management practices. Shifting cultivation over new climatically suitable areas, emerging because of climate change, may represent the most effective route of adaptation (Hannah *et al* 2013, Ceglar *et al* 2019b). This study aims to develop a climate suitability model for durum wheat and to assess the impact of climate change on future suitability.

2. Data and methods

2.1. Climate data

Daily data on maximum and minimum temperature, precipitation, and global solar radiation for the reference period (1981–2015) has been obtained from the global high-resolution AgERA5 dataset, available on the Climate Data Store of the Copernicus Climate Change Service (https://cds.climate.copernicus.eu). This dataset is based on hourly ECMWF ERA5 data on surface level, aggregated to daily time step and corrected towards a finer topography at a 0.1° grid (Boogard and Van Der Grijn 2020). The correction is based on variable-specific regression equations, trained on ECMWF's operational high-resolution atmospheric model.

Climate change projections are obtained from five CMIP6 climate simulations, statistically downscaled and bias-adjusted in the framework of Inter-Sectoral Impact Model Intercomparison Project (https://esg.pik-potsdam.de/search/isimip; Lange 2020): MRI-ESM2-0, IPSL-CM6A-LR, MPI-ESM1-2-HR, UKESM1-0-LL and GFDL-ESM4. The model simulations used for this study are based on the SSP126, SSP370 and SSP585 scenarios (Gidden *et al* 2019). SSP126 indicates SSP1 socio-economic pathway (world with strong economic growth via sustainable pathway) and target radiative forcing of 2.6 W m^{-2} at the end of the century. SSP370 depicts a future with high inequality between countries and within countries and a target radiative forcing of 7.0 W m^{-2} at the end of the century. SSP585 represents a future with strong economic growth based on fossil fuel pathway and the highest warming emissions trajectories (target radiative forcing of 8.5 W m^{-2} at the end of the century).

2.2. Current spatial distribution of global durum wheat areas

The current spatial distribution of the main global durum wheat production areas has been established based on information on growing regions provided by Barilla and International Maize and Wheat Improvement Center (CIMMYT). The spatial dataset provided by Barilla consists of the geographical presence of durum wheat on the global scale (figure S1 available online at stacks.iop.org/ERL/16/1040490/mmedia). The major production areas are concentrated around the Mediterranean (the Middle East, Maghreb and southern Europe), the Northern Great Plains of northern America, Central Asia and Australia (table 1). In northern America durum wheat is cultivated also in California, Arizona and north-western Mexico, where it is mainly irrigated. In the majority of durum wheat regions, spring durum wheat varieties without vernalization requirements prevail (Palamarchuk *et al* 2005, Gbegbelegbe *et al* 2017, Royo *et al* 2020). While, winter and facultative durum wheat varieties occupy substantially lower area and are mainly concentrated around the Mediterranean, Black and Caspian Seas.

The MIRCA2000 dataset of monthly irrigated and rainfed crop areas around the year 2000 (Portmann *et al* 2010) has been used to classify the current spatial distribution of global wheat areas according to the prevalence of either spring-sown (generally sown in late winter or early spring) or winter-sown (sown in autumn or early winter) wheat. Additionally, regions where wheat is predominantly irrigated or rainfed have been outlined.

As a prerequisite for the calculation of bioclimatic variables relevant for durum wheat, a crop calendar indicating sowing and harvesting months is necessary. Thus, we have intersected the spatial layer of global durum wheat areas (providing information on spatial extent of durum wheat) with MIRCA2000 spatial distribution of gridded wheat cropland area to obtain the spatial distribution of four different cropping categories: rainfed winter-sown wheat, irrigated winter-sown wheat, rainfed spring-sown wheat and irrigated spring-sown wheat. The resulting intersection provides the global cropland regions, where durum wheat is currently grown (figure S5).

We assume that the obtained intersected areas are suitable for durum wheat growth under current climate conditions. We should emphasize that even though we make a distinction between winter- and spring-sown durum wheat based on the prevailing

Table 1. Major global durum wheat areas in 2016/2017 season (source: CIMMYT).

Region	Country	Area (1000 ha)	Region	Country	Area (1000 ha)
Europe		2826	**Middle East**		2172
	Italy	1385		Turkey	1238
	Spain	449		Syria	603
	France	401		Iran	215
	Greece	400		Iraq	85
Central Asia		2660	**Maghreb**		2656
	Kazakhstan	1950		Algeria	1440
	Russia	470		Morocco	650
Northern and Central America		3724		Tunisia	451
	Canada	2367	**Australia**		250
	United States	957	**Rest of the world**		1720
	Mexico	400			

crop calendar, we do not distinguish between different existing varieties grown globally (i.e. winter, facultative and spring durum wheat varieties). Both the climate risk analysis and the suitability model, developed in this study, rely solely on the presence/absence of durum wheat.

2.3. Derivation of durum wheat crop calendar

The MIRCA2000 crop calendar was used to identify sowing and maturity months for the durum wheat growing areas (figures S6 and S7 for winter- and spring-sown durum wheat, respectively), by using the following assumptions:

(a) maturity occurs in the same month of the reported harvest;
(b) the period starting two months before harvest and ending with harvest corresponds to the anthesis-maturity period.

The adopted phenological dataset from MIRCA200 covers a very wide range of conditions representing the huge diversity of World climates (Zampieri *et al* 2017). The diversity of current climates has been shown to cover the local climate differences projected for the future, with the only exception of appearing extreme climates which are not going to be suitable for agriculture (Zampieri and Lionello 2010).

Exact sowing, anthesis, and maturity dates depend on the sown wheat varieties and farm-scale agro-management decisions. They are neither constant in space nor in time and their future evolution will be highly influenced by the pattern of development of the new varieties released by breeding programmes, and by adaptation strategies. These methodological choices and assumptions may be better understood by considering: data gaps on past and current sown varieties, computational resources limiting the possibility to build very large ensembles exploring the full space of possible varieties and agro-management strategies, and that we here aim at assessing climate-driven suitability. Dedicated future studies, also taking advantage of expected computational and modelling facilities that will become available (Bauer *et al* 2021), will be performed to overcome the aforementioned limitations while relaxing some of the critical assumptions.

2.4. Climate risk assessment

The risk of unfavourable climate events during the durum wheat growing season has been estimated for the reference period (1981–2015) and two periods in the future: 2031–2060 and 2061–2090. For this purpose we use the Clisagri agro-climate service tool, which has been built in a co-designed approach with durum wheat farmers and agronomists (Ceglar *et al* 2020). The Clisagri tool characterizes four groups of climate risks: drought, excessive wetness, cold stress and heat stress. Here, we have selected three risk indicators: drought stress during the entire growing season, drought stress between anthesis and maturity and heat stress between anthesis and maturity. Drought during the growing season can lead to reduced seed setting rate and reduced grain filling rate, resulting in lower total biomass per plant at harvest. Heat stress between anthesis and maturity can lead to sterility of florets (if occurring around anthesis stage), speed up the development and decline the photosynthetic rate (Porter and Semenov 2005, Akter and Rafiqul 2017).

Drought stress in Clisagri is estimated by the standardized precipitation evapotranspiration index (SPEI; Vicente-Serrano *et al* 2010). The SPEI is calculated for two different aggregation periods: sowing-maturity and anthesis-maturity. To better position the future drought intensity in parallel with the one in the reference period, the SPEI parameters are first calibrated for the reference period, and then used to calculate SPEI values in the future. Heat stress is represented by the number of days with maximum daily temperature exceeding 28 °C between anthesis and maturity. Heat stress event occurs each time the number of hot days exceeds the 75th percentile of values observed during the reference period (1981–2015).

Table 2. Description of bioclimatic variables used in this study as predictors for suitability model. All averages are based on first calculating mean values for the aggregation period of each year, and then performing the interannual averaging of these values.

Bioclimatic variable	Description	Aggregation period
BIO1	Average maximum temperature	Sowing–anthesis
BIO2	Average minimum temperature	Sowing–anthesis
BIO3	Average of global solar radiation	Sowing–anthesis
BIO4	Average ref. evapotranspiration	Sowing–anthesis
BIO5	Average precipitation	Sowing–anthesis
BIO6	Average maximum temperature	Anthesis–maturity
BIO7	Average minimum temperature	Anthesis–maturity
BIO8	Average of global solar radiation	Anthesis–maturity
BIO9	Average ref. evapotranspiration	Anthesis–maturity
BIO10	Average precipitation	Anthesis–maturity
BIO11	Maximum temperature of warmest month	Sowing–maturity
BIO12	Minimum temperature of coldest month	Sowing–maturity

The same thresholds are used to calculate heat stress events in the future. The extent of the area affected by heat stress is defined by summing the arable land where the number of hot days exceeds the 75th percentile observed during the reference period.

2.5. Suitability model specifications

2.5.1. Method selection

The suitability model is based on support vector machines (SVM). SVM is a widely used classification algorithm for nonlinear binary classification (Cortes and Vapnik 1995). As a class separation method, the SVM seeks for optimal separating hyperplane between two classes.

We use a set of 12 bio-climatic variables as model predictors, characterizing the growing conditions between sowing and maturity (table 2). The indicators are based on temperature, precipitation, global solar radiation and reference evapotranspiration and are structured according to literature review and expert recommendations. For example, global solar radiation has been found to affect plant height, cycle length and biomass production, while minimum temperature has an important effect on the number of tillers and spikes per unit area (Royo *et al* 2014). Evapotranspiration and rainfall were found to have a significant effect on kernel weight, final grain yield and the number of grains per m^2.

Before training the suitability model, we prepared the background sampling regions. We used the entire global arable land (Ramankutty *et al* 2008), representing global distribution of land that can be used to grow crops. To train the SVM model, the current durum wheat regions are assigned to class 1 (suitable) and the rest of arable land to class 0 (not suitable; figure S5). As a result, nearly 13% of the entire arable land is classified as suitable for winter-sown durum wheat, while this value falls below 3.5% for spring sown durum wheat. The implicit assumption, here made, is that durum wheat is currently cultivated in areas representing a climatic optimum for this crop. Of course, socio-economic factors, influencing crop cultivation, are not considered.

2.5.2. Model training and evaluation

Due to the selection of the entire arable land as background sampling, our dataset is characterized by highly imbalanced data, with the majority of arable land being not suitable for durum wheat. To address this issue (Akbani *et al* 2004), we implemented a hybrid multi-step approach. First, a different error cost SVM (with radial basis Kernel) based on the imbalance ratio is performed (Batuwita and Palade 2013). As a standard SVM would result in a biased (towards the minority class) hyperplane, this step provides a first correction. Then, a SMOTE-like oversampling is applied as follows. For each of the identified support vectors of the minority class, an oversampling is performed by using the five closest points (belonging to the minority class) in the feature space (i.e. using the Kernel-induced distance). According to the imbalance ratio, the support vector set is inflated by adding points lying between each support vector and the five closest points. Finally, a radial kernel SVM is applied to the new data set.

The cross-validation of the SVM models is performed by using 10-fold subsampling of training and testing data, with the model being trained on 90% of background sampling regions and evaluated on the remaining 10% in 10 replications. To measure the model predictive performance, we use the area under receiver characteristic curve (AUC) metric on the test dataset. The receiver characteristic curve (ROC) summarizes the trade-off between the true positive rate (the ratio of durum wheat locations that were correctly classified by the classification model) and false positive rate (ratio of non-wheat locations that were incorrectly classified) for a set of different probability thresholds. The ROC curve actually represents the graph of true positive rates against false positive rates for a series of cutoffs applied to predict the final class outcome. Any point above the 1:1 line in this graph represents a classifier that is better than the random one. The AUC summarizes the ranking of suitable locations (durum wheat presence) against the ranking of the background samples (remaining arable land) and therefore indicates how the derived model is able to distinguish between different classes (Bradley 1997). AUC ranges between 0 and 1; a value 0.5 indicates a model that is no better than chance, while higher values (approaching 1) indicate better model performance. In addition, we also calculate sensitivity (percentage of simulated durum wheat areas that are correctly identified) and specificity (percentage of non-suitable regions that are correctly identified). Both measures are suitable for the evaluation of classification performance, especially in the case of imbalanced data.

To measure the individual variable importance, we apply cutoffs to the predictor data and then calculate sensitivity and specificity to estimate the AUC (Kuhn 2008). The latter then represents a measure of variable importance. Nevertheless, we should stress that this approach gives an evaluation of individual features importance, while it does not address the redundancy between features.

2.5.3. Impact assessment

The original SVM model is derived from observed climate data for the reference period (1981–2015) to assess the model's predictive performance and obtain the optimal cost and gamma parameter values. The optimal set of parameter values are then used in subsequent steps to create SVM models for climate change impact assessment. The training of these models is performed based on the reference climate datasets from each of the five bias-adjusted GCMs. The models are trained for the reference period (1981–2015) and then applied for two future time periods: 2031–2060 and 2061–2090. To assess the consistency of SVM models trained on bias adjusted GCM data, the current spatial distribution of simulated suitability of each model is compared to simulated suitability of SVM model trained on the observed climate data (AgERA5).

3. Results

3.1. Changing climate risk in current durum wheat growing regions

The main global durum wheat growing regions are expected to experience unprecedented drought events in the coming decades (figure 1) throughout the entire growing season. The frequency of extreme drought events is expected to increase considerably already in mid-century especially over the current durum wheat areas of Europe, the Middle East, Maghreb, Russia, and central Asia. The difference between the three emission scenarios is small during the mid-century, but it increases considerably towards the end of the century; the increase in drought intensity under the low-end emission scenario SSP126 remains significantly below the ones associated with the high-end emission scenarios SSP370 and SSP585. What is today considered an extreme drought could become a near-normal (most frequently observed) event in the second half of the 21st century across major parts of the current global durum wheat regions under both SSP370 and SSP585 scenarios. The changes under the low-end emission scenario, while still being significant, are much lower.

As an effect of these projected changes, the proportion of durum wheat areas affected by extreme drought during the grain filling period is expected to considerably increase in all regions currently suitable for durum wheat (figure 2). The sharp future increase in rainfed and irrigated areas affected by extreme drought is more pronounced for southern Europe, the Middle East and Maghreb, mainly as a consequence of reduced precipitation and increased atmospheric evapotranspirative demand in areas surrounding the Mediterranean Sea. The currently negligible probability of observing more than 40% of European durum wheat areas being affected by extreme drought events in a single year, increases to roughly 10% in mid-century and nearly 50% towards the end of the century under the SSP585 scenario; slightly lower increase can be observed for the SSP370 scenario. Low-end emission scenario results in lower, however still significant, increase in areas affected by drought. Changes in the extent of extreme drought in currently irrigated areas indicate a substantial increase in water demand under the two high-end emission scenarios. The most pronounced increase is expected in the Middle East, which already has the highest share of irrigated wheat cropland (MedECC 2020).

Following the same pattern of drought, the areas affected by large-scale heat stress events are projected to substantially increase in the future under the two high-end emission scenarios. On the other hand, the SSP126 scenario demonstrates the added value of sustainable development in the future, with the increase in area affected by heat stress being substantially lower compared to the high-end scenarios. While the risk of the entire rainfed durum wheat cropland being affected by heat stress is currently zero in Europe, it increases up to 50% towards the mid-century, and to 100% at the end of the century under the SSP585 scenario. This risk remains negligible or very low under the SSP126 scenario. Similar changes are expected for the Middle East and the Maghreb; while less pronounced ones (although still very high) are projected for Australia and northern America.

3.2. Climate suitability for durum wheat

The most relevant climate conditions for winter-sown durum wheat suitability are linked to temperatures

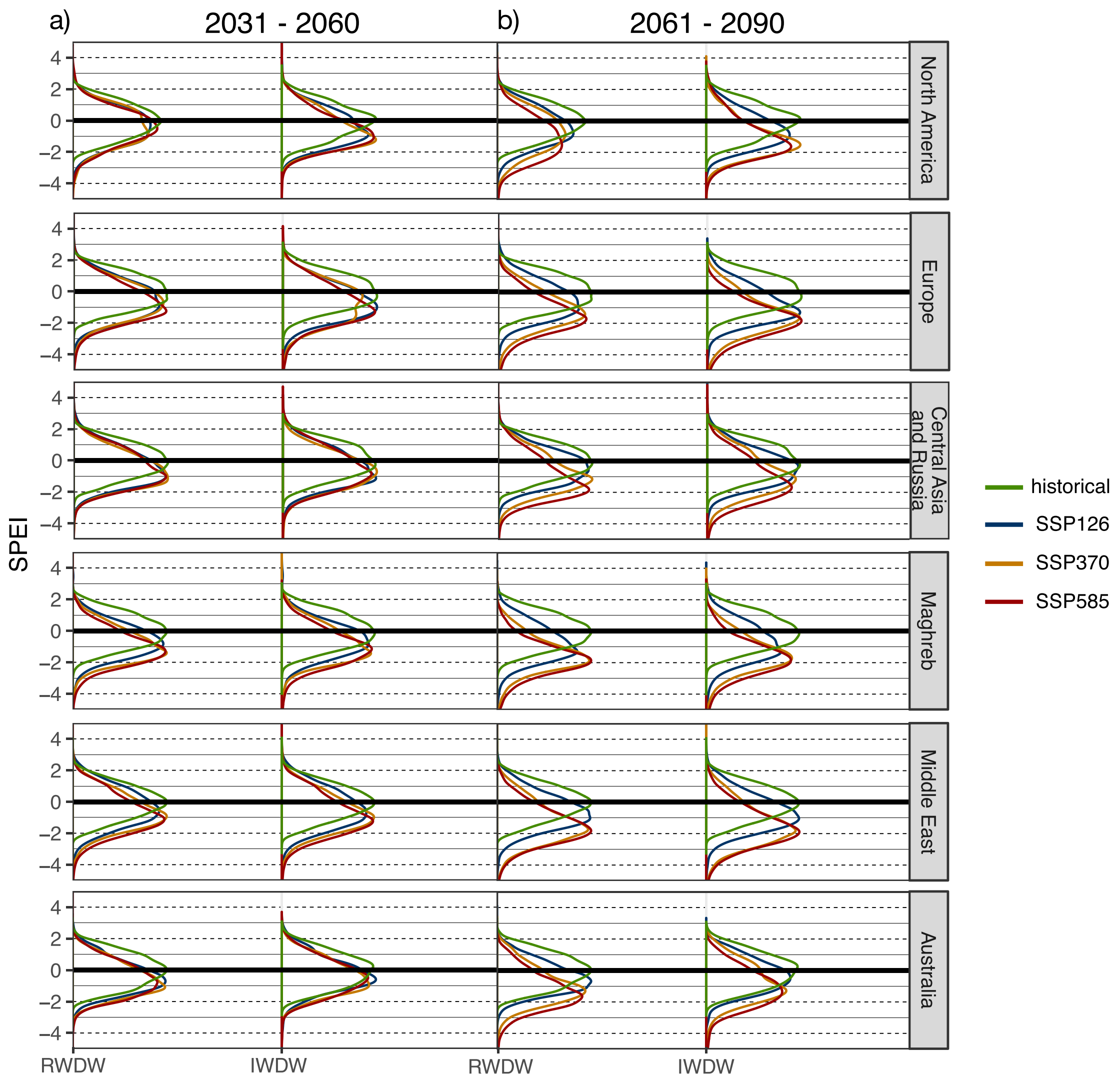

Figure 1. Projected hydrological changes estimated by using the SPEI over the main current durum wheat growing regions of the world. Two different cropping systems are spatially distinguished: winter-sown rainfed durum wheat (RWDW), and winter-sown irrigated durum wheat (IWDW). Three different scenarios are considered (SSP126, SSP370 and SSP585) for two distinct future periods: 2031–2060 (a) and 2061–2090 (b). Each graph also contains historical SPEI distribution for comparison purposes.

from sowing to anthesis (figure S2). Suitable areas are characterized by generally lower minimum and maximum temperatures between sowing and anthesis. The wide range of temperatures suitable for durum wheat is a consequence of the spatial distribution of suitable areas and the growth habit of cultivated varieties. Climate conditions of the suitable areas go from continental climate regimes (such as central Ukraine and central Asia) to Mediterranean climate. The distinction between these two climatic areas can be observed also in the temperature probability distribution, which is characterized by bimodality in the three most important bioclimatic variables. On the other hand, non-suitable areas are characterized by a single peak in the warm temperature range, belonging to arable land in tropical areas. High importance is also identified for precipitation, global solar radiation and minimum temperatures between anthesis and maturity (figure S2). Generally, similar variable importance can be deducted for spring-sown durum wheat suitability (figure S3). The latter is mainly determined by global solar radiation between anthesis and maturity, as well as minimum temperature from sowing to anthesis.

The small differences in the estimated importance of the single bioclimatic variables point to the need of integrating all of them into the development of a suitability model. Furthermore, it confirms the necessity of variable pre-selection, here largely based on literature review. Solar radiation was found to have significant effects on crop cycle length, plant height and biomass production; while, minimum temperatures influence the number of tillers and spikes per unit area of spring durum wheat (Royo *et al* 2014). The varieties grown in the identified suitable regions have likely adapted to different climate types; bioclimatic variables of higher importance might therefore have spatially varying effects on crop bio-physical

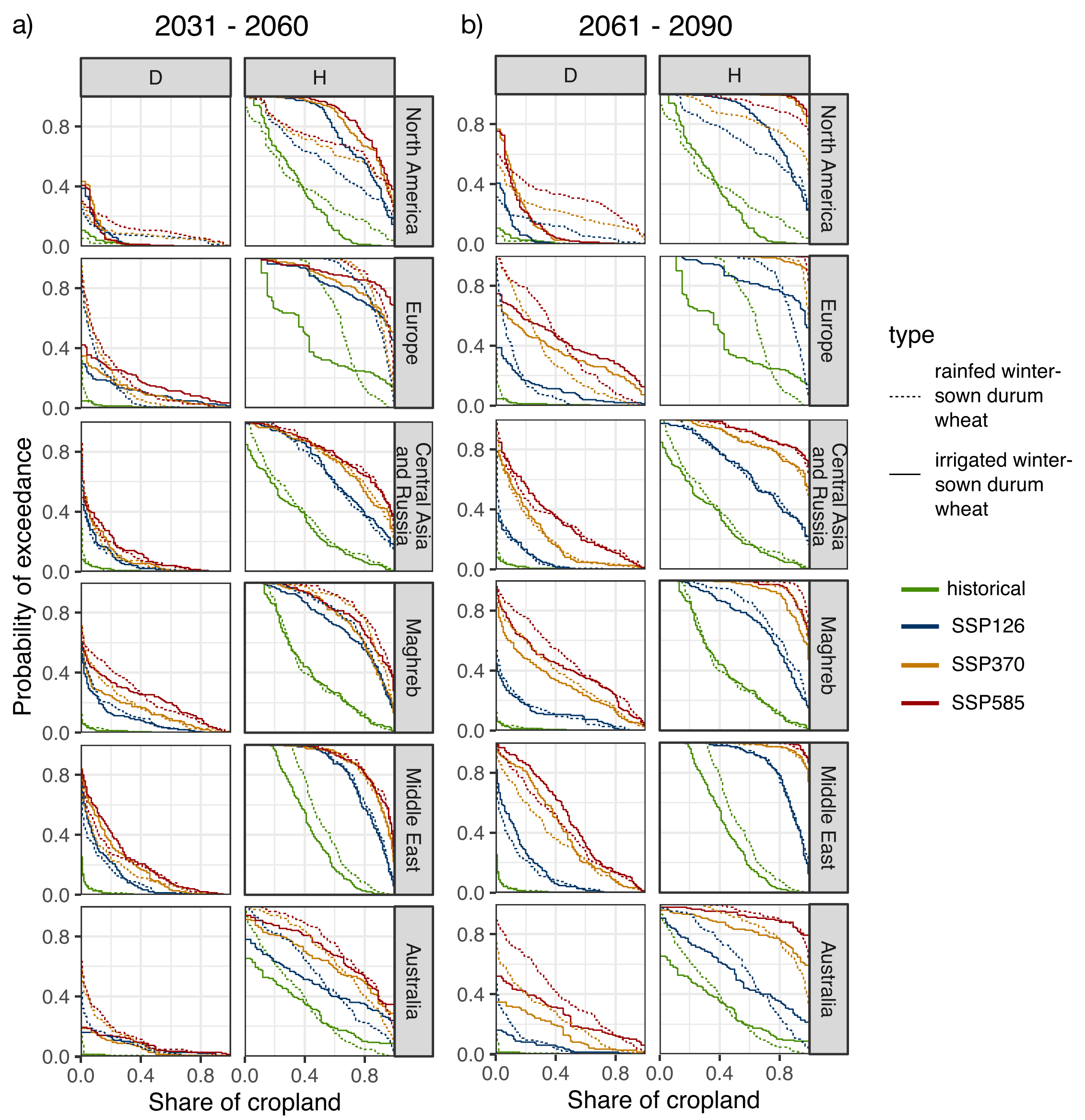

Figure 2. Projected changes in durum wheat areas affected by extreme drought (D) and heat stress (H) between anthesis and maturity. The probability of exceedance indicates the probability that a certain percentage of the wheat area (shown here as the share of the current wheat cropland in the main global durum wheat regions) will be affected by extreme drought and heat stress. Three different scenarios are considered (SSP126, SSP370 and SSP585) for two distinct future periods: 2031–2060 (a) and 2061–2090 (b). Each graph also contains historical SPEI distribution for comparison purposes.

characteristics. For example, low minimum temperatures favoured the formation of large kernel number of spring durum wheat grown in northern Spain, but the insufficient radiation during the grain filling limited the kernel weight. In contrast, spring durum wheat grown in northern Mexico developed a lower number of kernels due to higher minimum temperatures, but kernel weight was higher due to high levels of solar radiation (Villegas *et al* 2016).

The suitability model, trained and tested under the reference (recent past) climate conditions, is characterized by a good predictive performance, as it performs much better than chance at distinguishing the durum wheat presence from the background (global arable land). The model sensitivity, showing the share between correctly classified durum wheat grids and all grids with the presence of durum wheat, is 87% for winter-sown and 82% for spring-sown durum wheat. The model specificity, indicating the proportion of non-suitable areas that are correctly identified, is 99% for both winter-sown and spring-sown durum wheat models. Figure S4, showing the observed and modelled suitability (based on observational gridded dataset), confirms the good predictive model performance. With several misclassifications in the margin areas of suitable zones, especially in southern Spain and Russia, the model accurately predicts the current distribution of suitable regions.

To assess the impact of climate change on future suitability, five different suitability models are used, each of them being trained by using different climate model simulations. As the simulated climate data are bias-adjusted towards the observational dataset (see section 2), the resulting suitability distribution of the

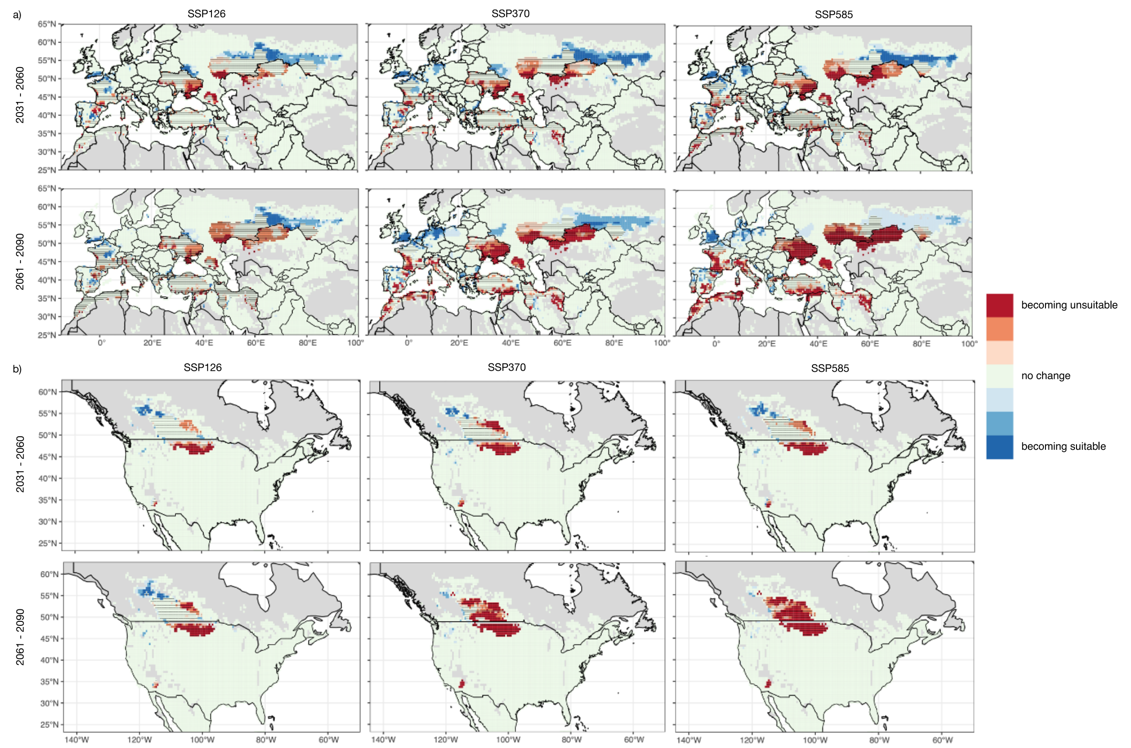

Figure 3. (a) Estimated impacts of climate change on rainfed winter-sown durum wheat suitability across Europe, Middle East, and central Asia for three different scenarios (SSP126, SSP370 and SSP585) and two distinct future periods (2031–2060 and 2061–2090). Blue (red) colors indicate increasing (decreasing) suitability in the future. The different classes are based on the number of GCMs that agree on the change of suitability; light blue (red) is used when at least three GCMs agree, while dark blue (red) when all GCMs agree. Hatched areas indicate the current distribution of rainfed winter-sown durum wheat. (b) Same as (a), but for spring-sown durum wheat in northern America.

five different suitability models closely matches the one of the model trained on the observational dataset (as well as the observed suitability distribution; figure S5).

The most significant projected loss of suitability for winter-sown durum wheat in the mid-century appears in eastern Ukraine, European Russia, and Kazakhstan under all three emission scenarios; losses are also evident in southern France, Spain, northern Italy, Morocco, and southern Turkey, especially under the two high-end emission scenarios (figure 3(a)). The difference between low-end and high-end scenarios becomes substantial in the second half of the century, when high-end emission scenarios lead to pronounced loss of suitability in southwestern France, northern Italy, southern Turkey, and the Maghreb. While the changes in simulated suitability under the SSP126 scenario remain substantially smaller. Suitable zones are projected to move further north in Europe and central Asia under all three emissions scenarios. The climate may become suitable in many regions of central and western Europe, such as: north-eastern Iberia, England, northern France, northern Germany, and northern Poland. The largest gain in suitability (at mid-century) can be seen in the south-western Siberian and southern Ural federal districts of Russia. Negative impacts on winter-sown durum wheat suitability are expected in the North American Great Plain (figure S8). Nevertheless, arable land in north-western United States will become climatically suitable, compensating for the loss in the Northern Great Plains. In Australia, large regions may become unsuitable, while a significantly smaller proportion of arable land will become suitable towards the second half of the century (figure S8).

Canada, currently one of the most important global durum wheat producers, may experience large-scale suitability losses for rainfed spring-sown durum wheat especially during the second half of the century (figure 3(b)) and under the two high-end emission scenarios. At the same time, very limited areas north of the current production regions are projected to become suitable. SSP126 scenario results in substantially lower suitability losses, limited mainly to the southern part of the current spring-sown durum wheat production areas. The same scenario also results in higher gain in suitability in the regions north of the current production areas. Loss of climate suitability for rainfed spring-sown durum wheat is projected also for southern Spain and several regions of northern Africa, more pronounced under the two high-end emission scenarios (not shown).

Decrease in suitable areas for winter-sown rainfed durum wheat towards the mid-century is mostly visible for latitudes below 30° S, and between 45° N and 55° N (figure 4(a)). While the latitudinal distribution

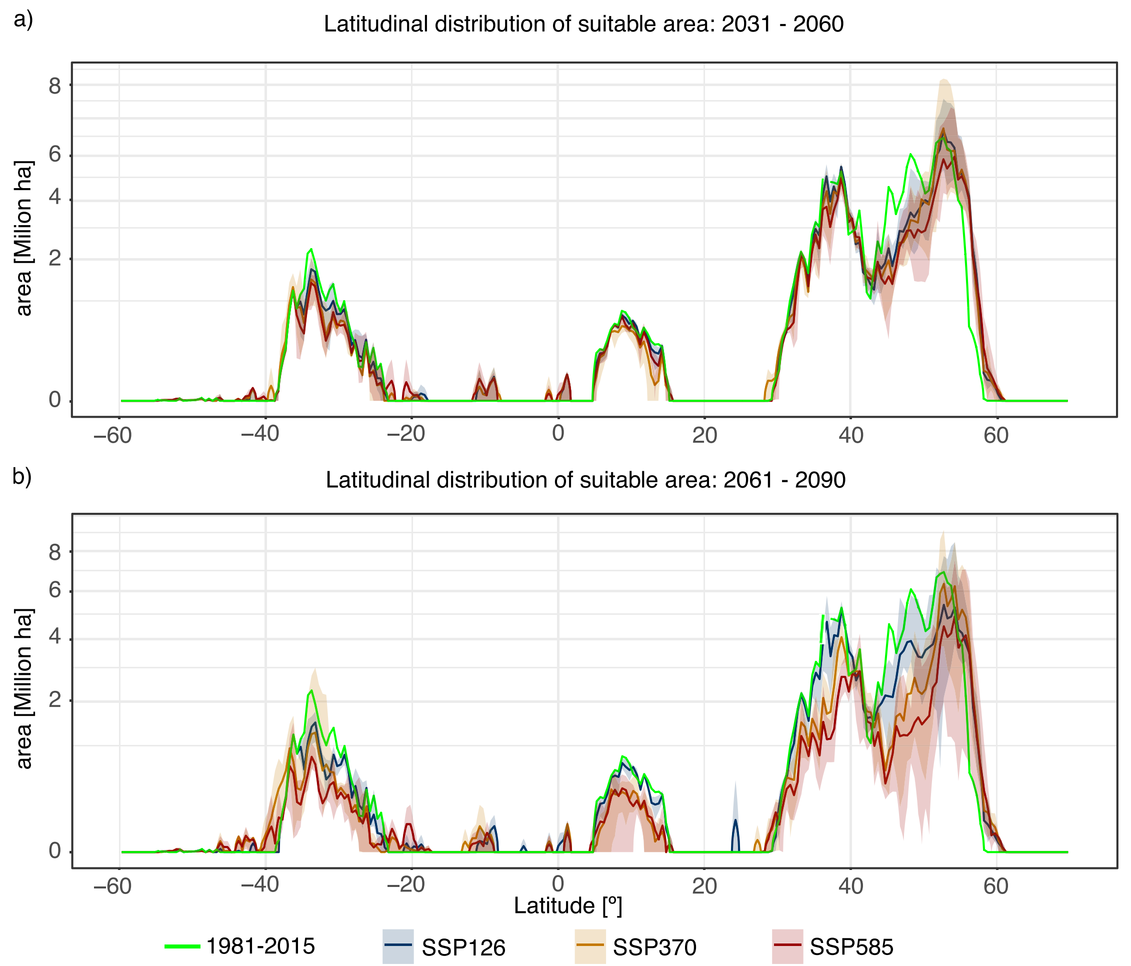

Figure 4. (a) Latitudinal distribution of current and future (2031–2060) suitable areas for rainfed winter-sown durum wheat. The area is calculated by summing the entire arable land area within suitable zones for different latitudinal 0.5° belts. Three different scenarios are considered: SSP126, SSP370 and SSP585. (b) Same as (a), but for the 2061–2090 period.

of suitable areas is generally comparable at the mid-century among all emission scenarios, it tends to diverge towards the end of the century (figure 4(b)). The cumulative loss of suitable areas is substantially higher for the two high-end emission scenarios (SSP370 and SSP585). Generally, suitable areas above 45° N exhibit a clear shift towards the north, most marked during the second half of the century for all the three emission scenarios. A pronounced decrease in suitable areas can be seen for spring-sown durum wheat (figure S9), especially under the two high-end emission scenarios. The sharp drop throughout the 21st century is mainly a consequence of suitability loss in the North American Great Plain.

4. Discussion and conclusions

Climate change is expected to significantly increase the drought and heat stress risks over all current durum wheat production regions, but most significantly in southern Europe, the Maghreb, and the Middle East. Increasing risk of climate extremes will translate into increased risk of yield losses in the Mediterranean, with CO_2 fertilization effect likely not being able to counterbalance the negative trend (Ferrise *et al* 2011, Dettori *et al* 2017, Feyen *et al* 2019). Even though the increased risk of drought represents the dominant pattern of future changes in the current production regions, northern America and central Asia will also experience high risk of extremely wet events.

Our study clearly demonstrates the importance of limiting global warming to levels well below 2 °C at the end of the century, which would substantially limit the loss of suitable areas globally for both, winter- and spring-sown durum wheat. The progressive loss of climatic suitability in several important Mediterranean regions towards the end of the century will require effective adaptation strategies (Zampieri *et al* 2020). The supply–demand equilibrium will be challenged also by the substantial loss of suitability for rainfed spring durum wheat in Northern America, which is currently the main durum wheat exporter to Europe. Given the high traditional and dietary importance of durum wheat, the need for implementation of different response mechanisms under future climate will be crucial to meet the demand side. One of the obvious adaptation measures is the spatial redistribution of crops and varieties (Ceglar *et al* 2019b), a process that is often inherently adopted by farmers (Baloch *et al* 2017). Our results support from a climate point of view such a strategy; although its socio-economic challenges should be carefully analyzed. However, our analysis also reveals how the overall arable land area climatically suitable for durum wheat will decrease considerably in the future.

The suitability projections for the future are here based on the assumption that durum wheat cultivation will remain within the limits of the current arable land extent, thus relying on sustainability principle. Nevertheless, there is a growing concern that agricultural land use activities are likely to expand beyond the current spatial extent due to growing demand for food, fiber and energy (Hurtt *et al* 2020). Modelling studies suggest that climate change is likely going to intensify competition for land in the future (Smith *et al* 2010). Furthermore, shifts in climate suitability might lead to competition for cultivating different crops in emerging suitable areas. According to the SSP585 land use scenario, which is based on strongly increasing food and feed demand and intensified livestock production systems (Hurtt *et al* 2020), the C3 annual crops will occupy approximately 60% of arable land suitable to grow durum wheat in the future (figure S10). This points to crop competition likely to occur in those emerging areas modulated by socio-economic demand.

Maintaining or even increasing the current durum wheat production level under increasing demand-side (Leegood *et al* 2010) with a growing population will require not only the exploitation of emerging suitable areas but also the development and implementation of effective sustainable adaptation strategies (Beres *et al* 2020). Durum wheat Mediterranean landraces can be considered as valuable resources to increase the genetic diversity for various traits of future cultivars, allowing more efficient adaptation in regions with increased risk of abiotic and biotic stress factors (Royo *et al* 2014, Soriano *et al* 2018, Maccaferri *et al* 2019). Even though some uncertainties still remain in understanding the effects of elevated CO_2 on crops, especially with concentration higher than 600 ppm (Toreti *et al* 2020), experimental efforts have already been able to identify wheat cultivars that may respond well to higher temperature stress while taking full advantages of elevated CO_2 concentration (Sabella *et al* 2020).

While implementing adaptation strategy, other economic factors should be also considered. The cost of keeping the production in the regions projected to become unsuitable in the future may, indeed, become too high. Climate change will increase irrigation water requirements in the Mediterranean, the Middle East, central Asia, and the North Great Plain of northern America (Konzmann *et al* 2013). The expansion of irrigation systems in these regions will be constrained by projected reductions of water availability and increasing water demand from other sectors (Elliott *et al* 2014, EEA 2016).

The central European and Asian regions (mainly southern Siberia), followed by north-western United States, might become essential for providing stable grain production and food security. Relatively low yields of wheat currently grown in central Asia can be improved by using modern varieties, technologies and economic incentives (Morgounov *et al* 2018), further compensating the loss of suitability in several important producers. Advancing technology, expanding the diversity of resilient wheat varieties and number of wheat rotations will represent important adaptation measures to cope with suitability losses (Beres *et al* 2020).

While moving production to emerging suitable areas is one of the options for an effective global adaptation, sustainable changes in food value chains will need to be considered (FAO 2019) due to interlinkages between: food production and safety; natural resources and agriculture; local economies, development patterns and agriculture. Adaptation should ensure farmers' production capacity and value as well as well-being. At the same time, adaptation should also allow food processors to offer products that combine best performance with low environmental impact (Kempa 2013). The latter will require a high level of flexibility to maintain current (where possible) and allow for new product explicit indications related to cultural issues, geographical origin and environment. Food processors can play a significant role in this by allowing for experience and knowledge sharing on sustainable agricultural practices amongst chain, scientific and technical operators (Blasi *et al* 2015).

Our approach to assessing climate suitability is based on a static crop calendar due to the limited availability of variety dependent data for dynamic phenological model calibration at the global scale. Consequently, we do not consider any dynamic response in anthesis and maturity dates in the future. This may influence the impacts of climate extremes under future climate conditions, which will likely (if no adaptation takes place) shorten the growing period for durum wheat. Nevertheless, our method based on global application of the SVM machine learning algorithm accounts for a redistribution of the current range of grown varieties. For example, varieties currently grown in regions with long-term average maximum temperature ranging between 20 °C and 30 °C (from anthesis to harvesting; figure S2) may follow the shift of climate zones having this temperature window (e.g. Ceglar *et al* 2019b). Currently suitable regions which will become warmer than the above-mentioned range may lose the potential to grow currently prevailing durum wheat varieties, but adaptation options (that are not considered in our study and would need benefit-to-cost and feasibility analysis) might be put in place to reduce the impacts of extremes during the grain filling period.

The proposed machine learning algorithm, building on essential climate variables, can be considered as a first step towards the assessment of suitability (not just from a climate point of view) for global durum wheat areas. Future efforts are needed to establish a spatially explicit global durum wheat variety distribution and selection process which would allow for more accurate simulation of sensitive growth phases as a response to varying climate conditions during the growing season (e.g. Zhou and Wang 2018, Ceglar *et al* 2020). The availability of spatially explicit parameters, required to run such phenological models, is currently resulting from field experiments. Existing parameterizations on continental level generally consider only winter soft wheat (e.g. Ceglar *et al* 2019a).

The climatic suitability approach here implemented integrates only climatic factors. To overcome this limitation, other agricultural, environmental and socio-economic factors should be considered in future studies such as soil types, feasible agro-management practices, infrastructure investments (such as irrigation), changes in the supply and processing chain, and economic profitability.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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