Assessing the impacts of recent-past climatic constraints on potential wheat yield and adaptation options under Mediterranean climate in southern Portugal

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Abstract

Wheat yield potentials under rainfed Mediterranean conditions have been long limited by late-in-season occurrence of enhanced water deficits and high temperatures, coinciding with sensitive reproductive stages. Present study aims to quantify and separate the impacts of two main abiotic stresses (drought & heat) on potentially attainable wheat yields, in a typical Mediterranean environment of southern Portugal (Alentejo) over 1986—2015. We also evaluate how possible adaptation options could mitigate potential yield losses (reduce the gap between actual and potential yield). Previously calibrated STICS soil-crop model is used for these purposes, which has been satisfactorily evaluated herein for yield simulations using additional field data before running at regional level. By coupling with high-resolution gridded soil and climate datasets, STICS simulations reliably reproduce the inter-annual variability of 30-year regional yield statistics, together with reasonable estimations of experimental potential yields. Therefore, the model is useful to explore the source of yield gap in the region. The quantified impacts, though with some uncertainties, identify the prolonged terminal drought stress as the major cause of yield gap, causing 40–70% mean potential yield losses. In contrast, a short-duration of crop heat stress (≥38°C) during late grain-filling phase only results in small-to-moderate reductions (up to 20%). Supplemental Irrigation (SI) during reproductive stages provides good adaptive gains to recover potential yield losses by 15–30%, while the proposed early-flowering cultivar is more useful in escaping the terminal heat stress (5–15% adaptive gains) than avoiding prolonged drought stress. In addition, advancing sowing date generally favours wheat production with a robust spatial-temporal pattern. Therefore, combined options based on application of SI, using balanced early-flowering cultivar and early sowing date, may contribute to considerably reduce local yield gap, where current yields can account for 60% of potential yields (26–32% without adaptation). Regional impact assessment and adaptation modelling studies are essential to support agricultural policy development under climate change and variability. The recommended combined adaptation may also represent a promising adaptation strategy for rainfed wheat cropping system in other regions with similar Mediterranean conditions. However, the existing spatial-temporal variability of adaptation response highlights the need to address adaptation strategies at a more detailed local scale with better flexible design.

Keywords: Winter wheat, STICS, Regional crop modelling, Terminal abiotic stress, Yield gap, Adaptation strategy

1 Introduction

Improving potential production and reducing local yield gaps are crucial to continuous crop productivity gains under increasingly limited cultivation lands. This represents an important pathway to meet the projected increasing food demand by about 70–100% until 2050s, mainly driven by population and consumption growth (Godfray et al., 2010). Wheat (*Triticum aestivum* L.) is the staple food crop and provide essential source of energy and nutrition for millions of people around the world. However, the global wheat grain yield is estimated to decline between 4.1% and 6.4% with 1°C global temperature increase under current conditions (Liu et al., 2016). For world´s major wheat producing regions, yield reductions due to higher temperature during grain filling alone, could substantially undermine global food security (Asseng et al., 2011). Moreover, high temperature episode can have larger negative effects with water-limited conditions, e.g. by creating high vapour pressure deficits with rapid depletion rate of limited soil water, resulting in very low leaf water potential and consequently leaf senescence (Farooq et al., 2011). In Mediterranean region, precipitation mainly concentrates during autumn and winter with mild temperature. The subsequent precipitation decrease and temperature increase in spring and summer, have substantially enhanced climatic water deficits, causing frequent drought stress during crop (wheat) late development phase (Pascoa et al., 2017; Saadi et al., 2015; Shavrukov et al., 2017).

The frequent occurrences of late-in-season water deficits and high temperature events, primarily overlapped with the critical crop reproductive stages, have long constrained wheat yield potentials under rainfed Mediterranean conditions (Asseng et al., 2011; Moriondo et al., 2010; Shavrukov et al., 2017; Yang et al., 2019). These climatic constraints can be further intensified with the projected overall warming and drying trend for the Mediterranean basin (Giorgi and Lionello, 2008), thus threatening the sustainability and resilience of wheat cropping system. Therefore, development of adaptation strategies are urgently needed, for which the research and innovation efforts should particularly focus on how to deal with more frequent drought and heat stresses during anthesis and grain-filling stages (Moriondo et al., 2010).

The combined adaptation strategy, by introducing adaptive cultivars and adopting efficient management practices, might be one of the most effective solutions (Ruiz-Ramos et al., 2018). Early-flowering cultivars, associated with rapid crop development and quick transition to the reproductive phase, represent a successful terminal stress escaping strategy for wheat production under Mediterranean environments (Shavrukov et al., 2017). Such cultivars tend to have a short vegetative phase, resulting in an early completion of growth cycle prior to enhanced terminal stresses, in a process usually correlated with short-season genotypes. Under favourable conditions, early-flowering/maturity trait can limit grain yield potential due to a shorter growth duration with less time for capturing light, nutrients and water. Despite such trade-off, a gradual shift towards using early-flowering wheat varieties has been observed over the last century in countries with Mediterranean-type climate, with overall yield benefits (Shavrukov et al., 2017). Moreover, the compromised yield potentials can be further ameliorated by introducing complementary traits of vigorous early growth, higher nutrient and water use efficiency (WUE), more biomass accumulation before anthesis and so on (Shavrukov et al., 2017). Along with early-flowering cultivar, adoption of early sowing date from a management perspective is also widely recommended for wheat adaptation to Mediterranean-type climate (Moriondo et al., 2010; Moriondo et al., 2011; Ruiz-Ramos et al., 2018). Anticipating growth cycle by early sowings, helps advancing the anthesis onset and shifting the sensitive reproductive phase to a cooler and wetter part of the season. Moreover, flowering timing is an important phenology event at which the high temperature episodes can occur with detrimental impacts, e.g. pollen abortion and sterile wheat seeds (Rezaei et al., 2018), which should be carefully optimized by combining appropriate cultivar choice with suitable sowing date. A wide range of phenology and sowing date combinations should be the starting point of any adaptation studies in Mediterranean environment (Ruiz-Ramos et al., 2018). Supplemental irrigation (SI) that supply additional water for rainfed crop during the drought-sensitive period, has also been suggested to be a promising adaptation option for wheat production in the Mediterranean region (Ruiz-Ramos et al., 2018; Saadi et al., 2015). SI during crop reproductive phase can mitigate the negative effects of drought stress on critical assimilate partition process, aiming to maximize WUE and stabilize crop yield with marginal to moderate yield losses (Oweis et al., 1998).

In practice, the effectiveness of adaptation options will depend on site-specific conditions due to spatial variations of climate, soil and management factors (Ruiz-Ramos et al., 2018). Although field experiments still represent the reliable steps in verifying the adaptation effectiveness, they are often limited by a few years and sites, under which the outcomes are difficult to be extended to a larger regional/national scale (Asseng et al., 2011). Process-based crop models, are proven to be useful tools for simulating complex genotype × management × environment interactions, providing crucial insights into understanding crop response to possible field-level adaptations according to certain environmental conditions (Rötter et al., 2018). Moreover, these simulation models are powerful tools to deal with multiple climatic factors and simulate their individual and interactive effects during various crop growth stages (particularly the sensitive stage) on final yield determinations (Asseng et al., 2014; Asseng et al., 2011). These features allow us to quantify and separate the impact of observed climate constraints on crop yields solely due to drought stress, from impact exclusively caused by heat stress. STICS is one of these models that simulate crop development and growth at daily timescale, taking into account the interactions among weather-crop-soil-management within cropping system (Brisson et al., 2003; Brisson et al., 2009; Brisson et al., 1998; Brisson et al., 2002). Though STICS is a generic model for various plant species, it was initially parameterized, tested and validated for cereal crops, e.g. wheat and maize (Brisson et al., 1998; Brisson et al., 2002). The predictive model performance for important output variables (e.g. aerial biomass, grain yield and soil water content), has been thoroughly evaluated over a wide range of agro-climatic conditions (including the rainfed wheat system × Mediterranean-type climate), showing an overall robustness and satisfactory accuracy (Coucheney et al., 2015).

Wheat cultivations are culturally, socially and economically important in Portugal, but insufficient domestic productions lead to the dependency on importations for satisfying internal demand (Almeida et al., 2016). The main wheat growing area is situated in the Alentejo region, southern Portugal, representing about 80% of total growing area and accounting for >75% of national wheat production (INE, 2019). In southern Portugal, though high temperature extremes are more or less relevant during the reproductive stage, water stress can occur with varying degrees of severity throughout the growing season, which should be taken as a whole (but still more pronounced during the reproductive stage). It is clear that climate-related risks for wheat production are substantially high in this region and thus need to be carefully addressed, both spatially and temporally. A previous study, conducted at one representative site within the region, suggested projected future climates are likely to have an overall negative impact on mean wheat yield (–27% to –14%), primarily driven by intensified drought and heat stresses during anthesis and grain-filling periods (Yang et al., 2019). Over the last decades, it was found out that regional wheat growing areas had declined drastically from an average of 211,104 ha (353,788 t) during 1986–1995 to of 47,394 ha (90,786 t) during 2006–2015 (INE, 2019). The reason for this increasingly low adoption, in addition to policy modifications, could be largely explained by observed trend towards a more arid climate type in Alentejo, adding serious concerns over yield returns and economic viability (as more investments and efforts would be required for a desirable yield) (Pascoa et al., 2017; Valverde et al., 2015). Therefore, it is important to quantify and understand to what extent of limitations the two main abiotic stresses (drought & heat) have been historically imposed on potentially attainable wheat yield, and how adaptation options could help overcome the limitations that are likely to be exacerbated under future climate change.

The current study is a continuation of the previous one (Yang et al., 2019), but instead of assessing impacts of projected future climate, we rather choose to focus on the past conditions using information on observed climate data, dominant soil types and relevant local management practices. As suggested by Challinor et al. (2018), calculation of adaptation effects in a changing climate should be better based on the difference of adaptation gains (compared to no adaptation) between projected future climate and current climate conditions, whereas the comparative advantage of adapted future period with respect to a non-adapted historical baseline is likely to result in an overestimation of adaptation benefits. Therefore, current study could pave the way for a more reliable and integrated regional impact assessment of prospective climate change. STICS model was previously calibrated for simulating local winter wheat yields using 5-year independently published field data (Yang et al., 2019), but the relevance of calibrated crop parameters should be further examined using additional representative datasets. Overall, we aim to (1) evaluate the performance of calibrated STICS model in simulating (harvest) yield of rainfed wheat cropping system using additional field trial data, before comparing grid-based yield simulations to regional mean yield statistics over 1986–2015 in Alentejo. (2) STICS model is further used to quantify and isolate the impacts of main climatic constraints (seasonal water deficits and high temperature extremes over grain filling) on potentially attainable yields over 1986–2015 in Alentejo. Finally, (3) a combination of proposed early-flowering cultivar with applied supplementary irrigation under a range of sowing dates, are examined as potentially appropriate adaptation measures in mitigating the yield gaps between actual and potential yields.

2 Data and methods

2.1 Study region and typical crop growth pattern

The study was performed for Alentejo plains region (Southern Portugal). The regional climate features a hot-summer Mediterranean climate, classified as “Csa” according to Köppen climate classification system (Köppen, 1918). Rainfed agriculture has maintained its dominant role in the region, despite growing interests for irrigation following the recent completion of the Alqueva dam and its ongoing expansion of irrigation network (Valverde et al., 2015). Common (winter) wheat was typically sown in autumn, from late October until mid-December, by direct drillings and harvested in June of next year (Almeida et al., 2016; Pascoa et al., 2017). Crop experienced vigorous early vegetative growth during mild and wet winter season when there was still adequate radiation, and the ideal heading date should be around April 1st ± 10 days to reduce the risk of spring frost damage (Almeida et al., 2016). Subsequent rising temperatures, accompanied by low water availability during grain-filling period, resulted in an early leaf senescence and consequently a very low harvest index before maturity (Almeida et al., 2016; Costa et al., 2013). Thus, the utilized STICS soil-crop model was expected not only to simulate correctly the wheat yield, but also to properly reproduce the typical growth pattern. Consequently, it can be a useful diagnostic tool for local wheat grain production.

2.2 The STICS soil-crop model

2.2.1 General description

Brief descriptions of main simulated processes in STICS (v8.5) relating to our studies were presented here, where more details of underlying model approaches and formalisms were given by Brisson et al. (2009). Crop phenology development was calculated based on accumulated thermal time, expressed as Growing Degree Days (GDD) with base temperature of 0℃ for wheat. Phenology can be slowed by sub-optimal photoperiod conditions, hindered vernalization fulfilment and effects of water and nutrient stresses. Subsequent phenology-driven leaf area growth determined photosynthetic active radiation intercepted by foliage, which then transformed into the aboveground biomass using the radiation use efficiency (RUE) concept (net photosynthesis). The following grain yield formation during grain-filling phase (anthesis to maturity) was calculated by applying a progressively increased harvest index (in analogous to a dynamic partition coefficient) to the accumulated aboveground biomass. Soil was divided into a sequence of several horizontal layers (maximum five), each of which was characterized by its hydraulic properties, bulk density and mineral and organic N content (if any). The soil and crop interacted via roots, for which the growth in root length and density was primarily a function of thermal time (phenology driven) and can be synchronized with aboveground shoot growth.

2.2.2 Water and heat stress simulations

As accounted for most of crop models, stress effects were abiotic stress only and simulated as reduction functions in STICS based on empirical relationships of limiting factor principles (Brisson et al., 2009). The water stress reduction functions (index), varying from 0 (extreme) to 1 (absence), were simulated as the ratio of crop available soil water content over root zone ($cm^3.cm^{-3}$), to crop water demand ($cm^3.cm^{-3}$) that primarily depended on the maximum transpiration rate, effective root density distributions over the soil and a physiological-function growth parameter (Brisson et al., 2009). The physiological growth parameter differed among physiological processes to represent varied drought sensitivities, giving rise to different water stress indices under the same soil water status. The phenology and leaf growth were affected by an index that was more sensitive to drought stress than an index governing photosynthesis and RUE. Leaf senescence, with senescent green leaf area and accumulated biomass losses, was considered less sensitive to soil water shortage. The associated senescent water stress index that accelerate leaf senescence was active mainly under severe water deficit.

Regarding heat stress for cereal crop, there were two main affected processes considered in the model, namely net photosynthesis and grain yield formation (Brisson et al., 2009). Photosynthesis was the most sensitive physiological process to elevated temperatures, where high temperature could impose Rubisco-related metabolic limitations and oxidative damages to chloroplast structure and function (Farooq et al., 2011). Such effects were simulated as a function of daily mean crop temperature, assuming optimal growth range between 12 and 17℃ (default settings), beyond which the adverse impacts gradually increased with a non-linear function until complete inhibitions of photosynthesis at temperature ≥40℃ (default threshold) (Brisson et al., 2009). Crop temperature was simulated in the microclimate module with an empirical approach, determined by air temperature, surface net radiation and actual evapotranspiration (Brisson et al., 2009). During grain-filling, the transportation rate of carbon assimilations from vegetative organs to grains could be substantially reduced upon exposure to high temperature (Farooq et al., 2011). To account for this effect, the model assumed a translocation threshold of daily maximum crop temperature (≥38℃) could temporarily halt the progression of grail filling (Brisson et al., 2009), which has been rigorously examined and verified for winter wheat (Majoul-Haddad et al., 2013). This threshold is particularly relevant in dry environment where limited surface evaporative cooling may lead to crop canopy temperature several degrees higher than ambient air temperature (up to 7℃) (Rezaei et al., 2018). Heat stress can also trigger senescence-related metabolic changes in wheat (e.g. breakdown of thylakoid components), resulting in hastened leaf senescence (Farooq et al., 2011). This effect can be implicitly simulated via the link of phenology module with relevant simulation processes, e.g. high temperature drove fast the phenology development rate that in turn accelerated natural leaf senescence (Brisson et al., 2009).

2.3 Input data for STICS model

2.3.1 Soil data

Harmonized World Soil Database (HWSD, v1.2) was used to supply the information on the spatial distribution of some required soil properties. HWSD was a comprehensive integration of several regional, national and global soil databases, providing fine-resolution (~1 km) soil profile data worldwide, stored as soil mapping units (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012). Within each mapping unit, the compositions of various soil units with different standardized topsoil (0–30 cm) and subsoil (30–100 cm) properties were available, in which only the dominant soil unit (the highest share of each mapping unit) was considered. The relevant soil properties were herein summarized in **Table 1**, together with estimation methods to assign values for corresponding model input parameters. For instance, a sensitive parameter for soil evaporation, was estimated based on particle size distribution using soil transfer functions proposed by Jamagne et al. (1977) (**Table 1**). Besides, some cultivation fields in southern Portugal feature shallow soil types with low fertility, long limiting the wheat yield potential (Almeida et al., 2016; Costa et al., 2013). To properly incorporate this feature, simulations of shallow soil occurred with either a reference soil depth of 30 cm or any presence of physical/chemical obstacles at a shallow depth (40–60 cm) limiting root growth. Both information were retrievable from HWSD (**Table 1**).

The required soil hydraulic properties listed in **Table 1** were derived from another database, namely EU-SoilHydroGrids 1 km (v1.0), which provides European-wide estimates of soil hydraulic properties at seven standard soil depths (up to 2 m) using commonly available soil physical properties and the European pedotransfer functions (Tóth et al., 2017). Following the extracted hydraulic properties at different soil depths, the average values over topsoil and subsoil were calculated by deriving a weighted average within the depth interval using the numeric integration method (i.e. trapezoidal rule) (Hengl et al., 2017; Tóth et al., 2017). Other important soil properties required by STICS, namely the soil organic N content and bioactive soil depth for mineralization, not usually available in many databases, were set to be constant in accordance with our previous site-specific study conducted in southern Portugal (Yang et al., 2018).

2.3.2 Climate data

Required weather variables consisted of daily surface minimum and maximum temperatures (°C), precipitation (mm), shortwave radiation (MJ m^{-2} day^{-1}), wind speed (m s^{-1}), actual vapour pressure (mbar), potential evapotranspiration (PET, mm) and atmospheric CO_2 concentration (ppm). The study period was defined as 1986–2015, corresponding to the 30-harvest years (simulation was initialized at 1985). For these years, temperature and precipitation data were obtained from E-OBS v17.0 (www.ecad.eu), a pan-European daily observational gridded data set (~25 km) that derived from spatial interpolation of dense weather station networks with a temporal coverage from 1950 to present (Cornes et al., 2018; Haylock et al., 2008). It has assimilated data series from approximately 3,700 and 9,000 weather stations for temperature and precipitation, respectively, but the station density varied greatly across the domain with comparatively fewer stations in southern Europe (Cornes et al., 2018). Regarding other variables, sub-daily datasets of surface downward shortwave radiation, 10-m wind speed and 2-m dew point temperature were firstly downloaded from ERA-interim (www.ecmwf.int), a global reanalysis of numerous climate variables spanning from 1979 to present, at an original resolution of ~80 km (Dee et al., 2011). However, the interpolated dataset (~12.5 km) was also available and chosen in our study. The extracted sub-daily data were then processed into either daily sum (radiation) or daily mean (wind speed and dew point temperature). The wind speed at 10 m was further converted into the surface value at 2 m following a logarithmic wind speed profile, whilst the surface dew point temperature was used to estimate actual vapour pressure based on the exponential function (Allen et al., 1998). PET was automatically calculated inside STICS according to the Penman method (Penman, 1948). Annual record of atmospheric CO_2 concentration over the study period was obtained from NOAA (www.esrl.noaa.gov/gmd/) and supplied as input relating to RUE subroutine (Brisson et al., 2009).

2.3.3 Harmonization of input data

To harmonize the soil and climate input that originated at different spatial resolutions, it would be necessary to divide the study region into regular horizontal grid cells, with a constant spatial resolution at 0.125° latitude × 0.125° longitude (~12.5 km). This resolution was chosen for our simulation units, as it was consistent with that of regional climate model simulations (EUR-11) from EURO-CORDEX (Jacob et al., 2014), which allowed us to further perform impact assessment of regional climate change. Besides, to avoid high computational burdens, the soil data was spatially aggregated from its original resolution of ~1 km to 12.5 km by sampling the most frequent soil type with interpolated hydraulic properties. The spatial distribution of Total Available Water (TAW, mm) over soil depth was presented, showing higher TAW (140–180 mm) in the western coastal zone than in the inner southeast areas (100–140 mm) (**Fig. S1**). As for temperature and precipitation, they were assumed spatially homogeneous at their original resolution (~25 km), thus containing four simulation units per 25 km × 25 km grid, whereas the remaining climate variables (radiation, wind and vapour) have retained their interpolated resolution (~12.5 km). Consequently, a unique combination of 30-year daily weather data and soil characteristics was completed for every grid cell of simulation unit covering the region.

2.4 Simulation setup

2.4.1 Statistical evaluation of STICS simulations at field-to-regional scale

The model performance was firstly evaluated in simulating actual (harvestable) grain yields, which were subject to substantial influence of seasonal drought and heat stresses over the past. For this purpose, annual statistics of average common wheat yields in Alentejo region over 1986–2015 were obtained from national statistical office (www.ine.pt) (INE, 2019). To conduct simulations at regional scale, it would be necessary to account for the input uncertainties regarding the spatial heterogeneities of cultivar choices and agronomic practices.

For regional crop modelling, it was assumed advantageous to define one regional adapted cultivar representative of the average characteristics of the numerous used cultivars (Jégo et al., 2010). STICS was previously calibrated for yield simulations using 5-year (1981–1986) published field trial data at one site within Alentejo, with a satisfactory grain yield prediction performance, i.e. R^2=0.9, MAE=464 kg/ha and nRMSE=20% (Yang et al., 2019). Refer to Yang et al. (2019) for calibrated crop parameter sets (adjustment of the generic RUE and definition of the cultivar choice). However, the robustness/representativeness of these calibrated crop parameters needed to be independently evaluated by using additional field observations. Based on two relevant journal publications (Calado et al., 2008; Costa et al., 2013), we had retrieved and assembled (bread) wheat yield trial data under a range of common cropping practices (sowing date + N fertilization rate & date/seeding rates) at three sites across the study region (**Table S1**). These yield data were particularly suitable for evaluation purpose, in that individual value represented the average yield of multiple (15 or 20) frequently used bread wheat genotypes/advanced lines in Alentejo (**Table 2**). Subsequently, it showed that the calibrated model was able to well reproduce (with all proposed statistical metrics) observed yield response to various experimental treatments, at sites with different soil characteristics and varying seasonal weather conditions (**Table 2**). The model performance was particularly good at Herdade da Revelheira where it represented half of the evaluation datasets, whereas slightly poorer performance (non-significant correlation but with good prediction accuracy) was found at Elvas (**Table 2**). It might be attributed to limited sample size at Elvas (as significant correlation occurred by joining all sites data), but also possibly due to lack of detailed input information regarding the irrigation scheduling (the only site with supplemental irrigation applied) (Costa et al., 2013).

Concerning the agronomic practices, different sowing dates (from Oct_30 to Dec_20 with 10 days interval), initial soil water contents (20% to 70% field capacity with 10% interval, depending on grid soil type) and N fertilizations (from 40 to 140 kg/ha with 20 kg/ha interval), were tested as a range of management inputs for every grid cell. These practices corresponded to the most relevant agronomic aspects for rainfed wheat cropping system in southern Portugal, and the initial soil water content was chosen to mimic the impacts of crop rotation strategies, where different preceding crops presented different water use patterns and soil water availability for the following crop (Carvalho and Basch, 1999). By varying these management input combinations (but with a constant set of calibrated crop parameters), the goodness-of-fit between 30-year yield statistics and simulations was assessed for individual grids covering the region, using multiple complementary statistical metrics. The evaluated statistical criteria included Pearson correlation coefficient (with significance test), mean absolute error (MAE, kg/ha) and normalized root mean square error (nRMSE, %). Simulations were considered to have an acceptable agreement when both significant correlation and low error class (defined as MAE≤600 kg/ha and nRMSE≤40%) occurred.

2.4.2 The impacts of main abiotic (drought and heat) stresses on potential yield

Besides modelling actual yields, simulations were also performed for potentially attainable yield (Y_p), water-limited (Y_w) and heat-limited potential yields (Y_h). Y_p was achieved in absence of any biotic and abiotic stresses with optimized farming practices, which was only determined by seasonal temperature, solar radiation, CO_2 level and genetic traits (e.g. growth duration) (van Ittersum et al., 2013). However, different sowing dates were able to affect Y_p as a result of influence on seasonal temperature and radiation, e.g. early sowing increased growth cycle due to less exposure to late-in-season hot days (Ruiz-Ramos et al., 2018). In STICS, the stress subroutines, including simulating water and nutrient stresses, heat stress, waterlogging effect and frost damage, were all switched off when simulating Y_p, while any biotic stresses were not assumed. Subsequently, Y_w was realized by solely enabling aggregated water stress effects over the season (**Section 2.2.2**) during Y_p simulation, in which crop growth was mainly limited by seasonal water supply and soil types (van Ittersum et al., 2013). Y_h was generated when Y_p only incorporated the extreme translocation temperature threshold on halting the grain filling (**Section 2.2.2**). Therefore, the stress impacts were quantified and calculated as the ratio of differences ($Y_w – Y_p$ or $Y_h – Y_p$) to Y_p, expressed as the percentage of potential yield reductions (calculated for individual years and grids). Nevertheless, potential yield losses attributing to sub-optimal high temperature on photosynthesis (**Section 2.2.2**) may occur throughout the growing season, but such effect was shown to be negligible (maximum reductions by

–4% where simulations were performed under different sowing dates to account for variations of Y_p) (**Fig. S2)**.

2.4.3 Tested adaptation options

Our previous analysis revealed that using early-flowering wheat cultivars (10–30% earlier relative to baseline) might be a suitable adaptation option in southern Portugal, in response to multi-model projections of consistently enhanced terminal water deficits and high temperature episodes, where mean yield gains were projected to be of 26–38% (Yang et al., 2019). However, given the known trade-off between terminal stress alleviation and shorter growth duration, a 20% reduction on GDD between emergence and anthesis in previously defined (calibrated) cultivar choice was chosen to mimic the adaptation option of using early-flowering/short-cycle genotypes. Similar setting with 20% reduction on phenology phase was previously adopted in CropSyst model to represent the short-cycle wheat genotype adaptation for a European-wide climate change impact/adaptation study (Moriondo et al., 2010).

Concerning the management adaptation, SI was implemented in the model by scheduling a constant irrigation amount of 20 mm (equivalent to 200 m^3/ha) per intervention, starting from April 1st until June 20th with 10 days interval (totalling 180 mm), a period largely corresponding to heading, flowering and grain-filling until maturity (Almeida et al., 2016; Costa et al., 2013). Besides, the simulated maximum crop temperature is possible to be reduced by irrigation-induced evaporative cooling (heat stress reductions) (Brisson et al., 2009), but the effects could be less evident without extensive and more frequent irrigation. Consequently, these two adaptations will depend on sowing date, where shifting sowing dates, either advanced (more favourite) or delayed, had been widely evaluated as possible adaptation options over Mediterranean region (Moriondo et al., 2010; Ruiz-Ramos et al., 2018). Therefore, the proposed adaptation options of using early-flowering cultivar and SI application would be separately and jointly (combined adaptation) evaluated under a range of sowing dates, in terms of how to mitigate the potential yield losses due to drought and heat stresses.

3 Results and Discussion

3.1 Regional climate characterizations

The Alentejo area is essentially characterized as a typical Mediterranean climate with irregular precipitation distribution and strong inter-annual variability, accompanied by frequent occurrence of a short period of high temperature during late spring (Almeida et al., 2016). The average annual mean temperature varies from 15.5 to 17.5℃ over the recent-past period (1986—2015), with a clear latitude gradient (**Fig. 1a)**. For a typical wheat growing season (October–June), the "hot days" (>30℃) mainly concentrate in April–June, being higher for eastern interior areas than the western coastal zone (**Fig. 1a)**. The annual precipitation pattern presents an approximate longitude gradient of higher precipitation in the coastal zone than in the innermost land (less than 500 mm) (**Fig. 1b)**. The wet season typically spans from October to March with the rest of the year being dry season, for which mean accumulated climatic water deficits during April–June reach –300 to –400 mm over 1986—2015 (**Fig. 1b)**. The high temperature episodes and the dry events are most likely to occur during April–June, coinciding with the late wheat development phase (i.e. anthesis and grain-filling), which constitute important climatic constraints for potentially attainable yields (Almeida et al., 2016; Costa et al., 2013; Pascoa et al., 2017).

3.2 Model test and evaluations against regional yield data

Following overall satisfactory model calibration and evaluation outcomes at field-level, the model can be confidently applied to a larger regional level, where the difference in the simulated wheat yields between sites and years can be essentially explained by the difference in soil characteristics and weather conditions. However, the spatial and temporal yield variations might not necessarily represent the best simulations against regional yield statistics, as considerable uncertainties exist with different management inputs. A preliminary three-way analysis of variance (ANOVA) for individual and interactive effects of the three management input factors (6 levels each) on the historical (actual) yield simulations, at randomly selected two sites over 1986–2015, has firstly been performed (**Table S2**). Although no significant interactive effects are found, they are individually significant: the sowing date explains most of the simulated yield variance, followed by initial soil water content and N fertilizations, respectively (**Table S2**). Local field experiments also demonstrated a relatively more important role of sowing date in determining wheat yield across a wide range of germplasms (both winter and spring wheat) (Costa et al., 2013). Though only two sites are tested with uncertain implications for the region, this preliminary analysis aims to narrow numerous possible input combinations at regional scale, i.e. testing them individually (6+6+6) by fixing the other two factors instead of a totalling 6×6×6.

The spatial patterns of goodness-of-fit with integrated statistical analysis, combining all proposed criteria (individual analysis is presented in **Fig. S3**) to select certain matching grid cells of the study region, reveals that Nov_20 appears to be the best-fitted sowing date for yield simulations against statistical data (**Fig. 2a)**. In practice actual sowing date varies year to year and mostly depends on the autumn rainfall, the lack of corresponding records for this sensitive parameter leads to fixed sowing date input every year across the region. Thus, it is not necessarily true that Nov_20 is the mostly practiced sowing date, but as a model input it results in a better simulation of observed yields. Nevertheless, the results can still suggest late sowing (late than Dec_20) is less relevant, which indeed is also a "not recommended" regional practice as it moves crop cycle towards situations with more terminal stresses (Almeida et al., 2016; Carvalho and Basch, 1999; Costa et al., 2013). Under fixed sowing date (Nov_20), varying initial soil water content from 40% to 70% field capacity (**Fig. S4** and **S5)** or N fertilizations between 40 and 140 kg/ha (**Fig. S6** and **S7)** can achieve a similar goodness-of-fit result (**Fig. S8**). Thus, a common Mediterranean agronomic situation (50% field capacity and 100 kg/ha N fertilization) together with adopted sowing date of Nov_20, result in a possibly best estimation of observed yields at the regional scale (**Fig. 2** and **S3**). However, the agreement between simulations and yield statistics is clearly less sensitive to a full range of N fertilization input (**Fig. S6–S8)**. This mainly results from the fact that N fertilization should be carefully optimized, taking into account seasonal rainfall distribution (to minimize winter leaching losses) and soil types (soil mineralization capacity) (Carvalho and Basch, 1995). Nevertheless, the irregular Mediterranean rainfall regime and the lack of reliable and detailed information for soil organic N content over mineralization depth, make this task very difficult, thus adding uncertainty to our simulations. Moreover, N uptake is often constrained under rainfed conditions with restricted yield response to high N amount, due to low soil moisture and transpiration flow (Oweis et al., 1998), which can be reflected in STICS by simulating a limited nitrate convection flow (Brisson et al., 2009).

STICS simulations proves to be able to well reproduce the inter-annual variability of 30-year statistical yields, with an acceptable level of estimation accuracy (**Fig. 2b)**. The remaining discrepancies can be partially explained by the influence of external factors (e.g. social-economic impacts) existed in the statistical data. It is also important to note such an agreement is based on a certain spatial pattern of yield simulations with a representative cultivar use and relevant (fitted) agronomic practices (**Fig. 2a** and **S3)**. The identified spatial pattern covers most of actual dryland arable areas in the region, except in the Northeast mountainous areas (**Fig. S9)**, for which more detailed measurements (e.g. field slope and thermal gradient with elevation) might be helpful to further improve our simulations. For the mean (1,664 kg/ha) and SD (463kg/ha) of regional yield statistics over 1986—2015, they are also very similar to those of simulated yields (1,670 and 567 kg/ha respectively) (**Fig. 2b)**. Furthermore, according to several regional experimental results obtained from the National Plant Breeding Station, the observed mean potential wheat yield over 1990–2010 is of 5,439 kg/ha (Almeida et al., 2016), very close to our simulated mean potential yield of 5,777 kg/ha (5,827 kg/ha during 1986–2015) (**Fig. 2b)**. The identified gap between actual and potential yields is highly consistent with a European-wide study using a different crop model (WOFOST), which highlights the highest wheat yield gap over 4,000 kg/ha is found in Portugal (Boogaard et al., 2013). The model ability to reproduce actual wheat yields, based on statistical data and reasonable simulations of experimental potential yields, may suggest it could be useful for exploring the source of yield gaps in the region, mainly relating to the frequent late season occurrences of high temperature and water shortage conditions (**Fig. 1)**.

3.3 Simulated seasonal crop growth pattern

Growth and development simulations at seasonal scale are investigated at three regional representative sites (**Fig. 3)**, which are empirically evaluated attempting to further verify actual yield simulations. Similar trends are obtained across sites despite small variation of extent, where model generally estimates a late anthesis timing (**Fig. 3)** given the suggested optimum heading onset around April 1st ± 10 days (Almeida et al., 2016). However, in practice, late heading can also be observed across cultivars (Costa et al., 2013). Additionally, the measured mean grain-filling duration (~38 days) among several frequently-used bread wheat genotypes (Dias and Lidon, 2009) has been successfully simulated for both early and late sowings (**Fig. 3)**, along with the simulations of typical harvest times (physiological maturity) in June (Almeida et al., 2016). Small biases in simulated phenology may not necessarily translate into errors in yield simulations, particularly a compensation mechanism exists between modelling pre- and post-anthesis processes (Asseng et al., 2014).

The general perception of grain-filling occurring at low water availability and high temperature, resulting in early leaf senescence with limited growth (Almeida et al., 2016), is also well reproduced irrespective of sowing dates (**Fig. 3)**. Simulated senescent water stress index, primarily triggered by severe crop water deficit (**Section 2.2.2**) (light to moderate levels are not shown), mainly occurs late in the season from the beginning of April (approximately beginning of leaf senescence) and tends to be progressively intensified until reaching a stable state (approximately complete leaf senescence) lasting till harvest (**Fig. 3a, b)**. In contrast, the risk of crop experiencing heat stress (≥38℃) mainly takes place over the very last development phase (from late May until harvest) (**Fig. 3a, b)**. Although both drought and heat stresses are more frequent and intense late in the season, it is important to understand their detailed distributions in terms of duration, probability and severity (Moriondo et al., 2011). Therefore, one important finding of present study reveals that late-in-season occurrence of severe crop water deficits tends to persist over a relatively long period (~two months), starting well ahead of grain filling, whereas heat stress mainly occurs within grain filling with a relatively short duration (<20 days). In both cases, detrimental effects are more pronounced under late sowing (**Fig. 3b)**.

3.4 Isolated impacts of drought and heat stresses at regional scale

As expected, drought stress appears to be the main limiting factor for potentially attainable wheat yields, representing a major source of yield gaps in the region, i.e. 40–70% mean potential yield losses covering most of the area for all sowing dates (**Fig. 4a)**. Climatic droughts, especially during grain filling and late ripening phases, have previously been identified as the major cause of rainfed wheat yield losses within the Iberian Peninsula, where concordance of low yield anomalies and dry events was found over 1986–2012 (Pascoa et al., 2017). Given the dominant role of drought, our study goes further by providing an estimation of the magnitude of the impacts, which, nevertheless, should be carefully interpreted. The drought-induced yield losses should implicitly include the negative effects of N deficiency, as potential yield gains by N fertilization are often smaller under limited soil moisture (Oweis et al., 1998). On the other hand, STICS, like many other crop models, does not exhaustively include all explanatory variables (with simplified approaches) in describing growth and yield formation processes under water-limited conditions. This is related to the model structure uncertainty (for the quantified impacts), which can be further addressed by using multi-model ensemble (Asseng et al., 2014; Asseng et al., 2019; Ruiz-Ramos et al., 2018).

In contrast, potential yield reductions exclusively due to heat stress during grain-filling period may have been less severe in the past, i.e. mostly moderate reductions (5–20%) over the inner east lands and under late sowing, while negligible over western coastal areas (**Fig. 4b)**. For evaluated heat stress impacts, the present study only considers affected processes relating to net photosynthesis (proves negligible, **Fig. S2**) and assimilate translocation during grain filling (**Fig. 4b)**, which may potentially neglect other important sources of temperature impacts. For instance, under elevated temperature (>30℃) during the late development phase (**Fig. 1a**), shortened grain-filling duration can reduce individual grain weight and final yields (Farooq et al., 2011). However, this effect is unable to be captured using the present approach, since both Y_p and Y_h simulations consider advanced phenology and reduced length of phenophase caused by high temperature that cancel each other during the calculation. Moreover, reduced grain number at temperature above 30 or 31°C during floret development or around anthesis in association with pollen abortions and sterile grains (Farooq et al., 2011; Rezaei et al., 2018), are currently not explicitly simulated (Brisson et al., 2009). All these may contribute to an underestimation of potential yield losses caused by heat stress, which require further model development with improved and advanced heat response functions (Rötter et al., 2018). Nevertheless, a noticeable yield loss up to 20% is discovered, which is expected to be amplified with projected higher frequency of heat events during sensitive stages (e.g. anthesis) throughout Mediterranean basin (Moriondo et al., 2010; Moriondo et al., 2011). Heat stress is thus likely to be as important as drought stress in limiting wheat grain yields with global warming trend (Asseng et al., 2019), despite a probably (comparatively) less pronounced role in the past.

Simulated spatial patterns are highly associated with their spatial distributions of observed climate and soil inputs, i.e. relatively higher yield losses over inner southeast areas where climate is warmer and drier (**Fig. 1**) with frequent soil types of low TAW (**Fig. S1**) and of presence of shallow root obstacles (not shown). Moreover, the yield impacts are also dependent on sowing date, where potential yield losses tend to be progressively increased from early (Oct_30) to late sowings (Dec_20 with the most widespread yield losses by 55–70%), as this gradually increases the risk of crop exposure to terminal drought and heat stress events (**Fig. 4)**. Advanced sowing time usually favours wheat productions over delayed sowing under typical Mediterranean conditions by advancing critical reproductive stages with less exposure to stressful conditions at the end of cycle (Carvalho and Basch, 1999; Moriondo et al., 2010; Shavrukov et al., 2017). However, the anticipation of growth cycle can be possibly constrained under climate change, due to either projected longer dry season lasting until autumn (Ruiz-Ramos et al., 2018) or the adversely affected crop vernalization fulfilment in response to a warmer climate during early sowing window (Yang et al., 2019).

3.5 Possible adaptation effects over 1986–2015

3.5.1 Supplemental irrigation (SI) under different sowing dates

Adaptation planning and modelling should target at minimizing the adverse impacts of identified terminal abiotic stress events (**Fig. 3** and **4)**. SI during sensitive crop stages shows good potential to recover potential yield losses by alleviating critical drought stress impact (**Fig. 5a)**, resulting in mean yield gains (mostly) of 15–30% across the region (difference between **Fig. 5a** and **Fig. 4a**, i.e. adaptive effects). Notably the positive effect is greater when crop is becoming more exposed to drought stress during sensitive growth stages, as seen in simulations with late sowing (Dec_20) where the widespread potential yield losses of 55–

70% (**Fig. 4a)** are successfully mitigated to a moderate level of 25–55% (**Fig. 5a)**. Due to the fact that rainfed cropping system is highly dependent on precipitation in the Mediterranean basin (Oweis et al., 1998), SI is widely investigated as a promising adaptation option under prospective warming and drying trends (Moriondo et al., 2010; Ruiz-Ramos et al., 2018). A single SI is sufficient to develop high yield adaptive potential in "Mediterranean South" wheat cultivation zone in Spain, allowing to overcome most of the detrimental effects of complex interactions among a wide range of temperature, precipitation and CO_2 perturbations (Ruiz-Ramos et al., 2018). The adaptation responses in current climate in terms of irrigation efficiency and yield gains (180 mm/season for 15–30%) are lower than those reported in an adaptation modelling study under a 2℃ warming scenario (120 mm/season for 41% averaged over Mediterranean basin) (Moriondo et al., 2010). This may indicate the SI advantages may be even higher under future climate. However, to support implementing this adaptation measure, ongoing expansion of irrigation infrastructure in Alentejo is essential (Almeida et al., 2016; Valverde et al., 2015), despite a growing competition in water allocation between Mediterranean agriculture and other sectors (Saadi et al., 2015).

3.5.2 Early-flowering cultivar under different sowing dates

The proposed early-flowering cultivar aims to avoid, at least partially, the enhanced water and heat stresses during late growing season. Over 1986–2015, the simulated 20% early-flowering cultivar results in mean advanced anthesis onset and grain filling by 13–17 days, with more pronounced effects in early sowing (**Fig. S10a)**. Delayed sowing date moves the crop cycle towards the most favourable period for vernalization, with earlier exposure to required winter chilling (Ruiz-Ramos et al., 2018), whereas crop tends to have a comparatively longer vernalization period with advanced sowing. As a result, the shortened pre-anthesis phase of early-flowering cultivar is more effective with early sowing (**Fig. S10a)**, because it enables more reductions of crop vernalization demand in days (as per GDD accumulation takes more days). Given the simulated advancements by days, the stress escaping strategy by adopting the proposed early-flowering cultivar is clearly more useful for avoiding terminal heat stress over a relatively short period than escaping the prolonged drought stress since early April (**Fig. 3)**. The partially avoided terminal water stress only generates net yield gains by about 0–4% across the region regardless of sowing dates (**Fig. S10b**). In contrast, quantified potential yield losses of 5–20% solely by terminal heat stress (**Fig. 4b)** almost completely disappear when early-flowering cultivar is introduced (noticeable improvements at late sowing), resulting in mean adaptive yield gains of 5–15% throughout the region (difference between **Fig.**

5b and **Fig. 4b)**. Notably, mean yield impact of heat stress (≥38°C) during grain filling over 1986–2015 may become negligible (0–5%), provided that the early-flowering cultivar was not sown late (before December) (**Fig. 5b)**.

In the Mediterranean environment, modern wheat varieties can display an earlier flowering onset by 10–13 days than old varieties over a century of breeding efforts, which are also considerably more productive by minimizing the risk of drought stress during anthesis and grain-filling stages (Shavrukov et al., 2017). However, the effectiveness of terminal drought escaping strategy is variable over the Mediterranean basin, being largely determined by the site-specific seasonal precipitation distribution and associated duration of dry spells (Ruiz-Ramos et al., 2018). In case of repeated and continuous dryness, the benefits can be considerably compromised causing impaired growth, unless crop switches its response to a more effective mechanism of drought tolerance (Shavrukov et al., 2017). Yet, the development of early-flowering wheat cultivar still proves to be a wise investment for Mediterranean area if global warming trend continues (Shavrukov et al., 2017). On one hand, it can help escaping the terminal heat stress, for which the frequency of occurrence was projected to have a widespread increase across the Mediterranean basin (Moriondo et al., 2010; Moriondo et al., 2011). On the other hand, the risk of spring frost damage during heading and anthesis, that largely limits the adoption of early-flowering cultivars in Portugal under current climate (especially when sown early) (Almeida et al., 2016), might be markedly reduced with projected increases in both minimum and maximum temperature (Yang et al., 2019). Additionally, the terminal stress escaping mechanism can be combined with strong early vigour traits to compensate for the biomass and yield losses of reduced growing length (Asseng et al., 2011).

3.5.3 Combined adaptation

When early-flowering cultivar is introduced with the application of SI over the sensitive period, simulation results show that the yield gap is markedly reduced: ratios of actual to potential yield averaged over 1986–2015 are mostly about 50–80% over the region (**Fig. 6**) and 26–32% (**Fig. 7a)** with and without the combined adaptation respectively. Moreover, a clear trend of increasing actual (adapted and non-adapted) and potential yields with gradually advanced sowing date, is consistently detected spatially and temporally (**Fig. 7a, b**). It confirms that combined adaptations based on early sowing provide good and wide adaptive potential (Moriondo et al., 2010; Ruiz-Ramos et al., 2018).

The spatial-temporal analysis also suggests that the simulated yield averages over the region and period (1986–2015) under combined adaptation consistently represent about 60% of corresponding potential yields for all sowing dates (but absolute yields are higher under early sowing) (**Fig. 7a, b**). However, there are considerable yield spatial and temporal variabilities, where the latter tends to be larger than the former irrespective of sowing dates (**Fig. 7a, b**), which primarily links to a stronger role of climate inter-annual variability than that of spatial climate variability. The adaptation responses (averages over 1986–2015) vary with different meteorological conditions and soil types throughout the region: higher adaptive gains (65–80%) in the wetter western coast areas but lower (35–50%) over the southeast interior areas with relatively warmer and drier climate and less favourable soil types (**Fig. 6**). Adaptation performances are only ineffective in very few grids, where the yield gap remains largely unchanged (actual to potential yield ratios are of 20–35%) compared to that (26–32%) without adaptation (**Fig. 6**). It can be attributed to the soil types of these grids, which are found to possess enriched clay content (heavy clay soil) with poor drainage. Irrigation water may only have effects on the topsoil (30 cm), such as the case already observed at local wheat cultivation fields (Costa et al., 2013). On the other hand, combined adaptation performs well in normal and wet years, but with exacerbated outcome in very dry years (regional averaged annual yield) over 1986–2015 (not shown but included in the box-plot of **Fig. 7b**). The assumed SI scheduling is largely ineffective to tackle the most severe and anomalously long dry spell (e.g. simulated leaf senescence begun much early before reproductive stage in 2005), while shortened growth duration with applied early-flowering cultivar only reduces yield potential. There is thus a strong need to develop a more robust and flexible SI scheduling to stabilize crop yields with maximized WUE, taking into account different local soil types and climate conditions, as well as the strong inter-annual variability and irregularity of Mediterranean precipitation.

In general, our findings are highly consistent with the results of a similar study conducted in another Mediterranean environment in northeast Spain, highlighting an overall high adaptive potential of SI for rainfed wheat cropping system, which should also be combined with other appropriate options, including the use of short-cycle or spring wheat cultivars and advocating the early sowing practice (Ruiz-Ramos et al., 2018).

4 Conclusion

Under rainfed Mediterranean conditions, wheat grain filling tends to occur with enhanced water deficits and high temperature (April–June), being recognized as the main climatic constraint and vulnerability for wheat production in southern Portugal (Alentejo). The present study represents the first attempt, to our best knowledge, to quantify and understand the contributions of main abiotic stresses (drought & heat) to potential wheat yield losses (gap between actual and potential yields) at (Alentejo) region scale. Following satisfactory model calibration and evaluation outcomes at different sites over multiple years, the STICS soil-crop model also shows capability to well reproduce the inter-annual variability of regional yield statistics over 1986–2015, taking into account spatial heterogeneity of climate conditions, soil characteristics and management practices. Reliable simulations are also obtained for the common seasonal growth pattern and for the experimental potential yields without abiotic stress. Therefore, the model is utilized to explore the source of yield gap in the region, mainly relating to the impacts of frequent terminal drought and heat stress events. Our study identifies crop drought stress as the major cause of yield gap in Alentejo over 1986–2015, which is largely associated with the detected prolonged duration of severe water deficit rather than the crop heat stress (≥38°C) that lasts for a relatively short period during late grain filling phase. However, uncertainties exist with respect to the possible underestimation of heat stress impacts, due to limited model ability to capture full range of heat response mechanisms. Note that biotic stress is generally of a lesser concern in Alentejo, due to the extensive use of disease-resistant genotypes and the dry environment that constrains the disease spread.

Although both drought and heat stresses are prone to be more frequent and intense during late wheat growing season under Mediterranean environment, it is essential to understand their site-specific distributions for designing target adaptation strategies. Across a range of sowing dates, the assumed SI during reproductive stages provides good adaptive potential to recover potential yield losses by alleviating the critical drought stress impacts. However, the SI benefits could be compromised in sites with soil types of poor drainage and in years with extreme drought events, which require the development of a more robust and flexible SI scheduling. Proposed early-flowering cultivar, accounting for the trade-off between shortened growth duration and reduced terminal stress impacts, appears to be more useful in escaping the end-in-season heat stress than avoiding prolonged terminal drought stress (with negligible benefits). By combining these two adaptation options at various sowing dates, it reveals a robust spatial-temporal pattern of an overall advantage for early sowing than for late sowing. Moreover, the early-flowering cultivar should be sown early to maximize the chance of success for effective terminal stress escaping strategy. Therefore, combined options based on SI during sensitive growth stages, use of balanced early-flowering/short-genotype cultivars and early sowing practice, may represent a promising adaptation strategy to mitigate the significant yield gap (likely widened under climate change) of dryland wheat cropping system for Alentejo, with important implications for the entire Mediterranean basin (particularly the southern region). However, a considerable spatial-temporal variability indicates adaptation response will highly depend on specific soil types and meteorological conditions (both climate mean and variance), highlighting the needs for adaptation strategies tailored to local conditions, and to account for a broad scope of options for a more flexible adaptation scheme (e.g. autonomous adaptation with changing climate).

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Table 1. Summary of important soil properties, observational source and approaches to estimate corresponding input soil parameters for STICS

Soil properties		Observed source	Estimation methods or assumptions to assign input values
USDA Soil texture	Sand (%)	HWSD	To estimate the cumulative potential soil evaporation limit (mm) as a function of sand or clay content (Brisson et al., 2009; Jamagne et al., 1977)
	Clay (%)		
	Silt (%)		To estimate dry soil albedo as a function of soil texture class (Brisson et al., 2009)
Soil layer division		HWSD	General assumption (topsoil=30 cm and subsoil=70cm) but modified by possible presence of shallow soil
Bulk density ($g\ cm^{-3}$)		HWSD	A direct input parameter
Surface calcium carbonate content (%)		HWSD	A direct input parameter
Soil surface pH (H_2O)		HWSD	A direct input parameter
Soil obstacle depth to root growth (cm)		HWSD	A direct input parameter
Surface slope degree (%)		DGTerritório	To estimate fraction of Hortonian runoff based on USDA CN curve method (Brisson et al., 2009)
Soil hydraulic variables	Volumetric moisture at field capacity (%)	EU–SoilHydroGrids	To estimate mean values over soil layers and convert into gravimetric water content
	Volumetric moisture at wilting point (%)		
	Saturated hydraulic conductivity ($mm\ day^{-1}$)		To approximate for infiltration rate ($mm\ day^{-1}$) at the base of each soil layer

DGTerritório (Directorate-General for the Territory) is an online database, mainly providing information on land use and land cover map in Portugal

Table 2. Soil characteristics, seasonal weather conditions and statistical evaluations of previously calibrated STICS soil-crop model performance in simulating local wheat grain yields (15% water content) at three sites (different from the calibration site) within the study region

Sites	Soil characteristics		Trial Year	T_{mean} (°C)	P_{recip} (mm)	Number of observed yields (Number of genotypes)	Statistical evaluation							References
	Dominant soil unit (FAO90)	TAW (mm)					*r*	R^2	RMSE (kg/ha)	nRMSE (%)	MAE (kg/ha)	MBE (kg/ha)	Slope	
Herdade do Louseiro	Vertic Luvisols (LVv)	142	1994–1995	14.9	293	4 (15)	0.9*	0.9	484	32	477	13	0.3*	(Calado et al., 2008)
			1996–1997	15.4	620									
Herdade da Revelheira	Dystric Regosols (RGd)	135	1998–1999	14.6	251	8 (15)	0.8*	0.6	421	18	371	–95	0.9*	(Calado et al., 2008)
			1999–2000	14.5	511									
Elvas	Chromic Cambisols (CMx)	84	2011–2012	14.2	257	4 (20)	ns	-	344	12	338	–11	ns	(Costa et al., 2013)
All Sites (overall evaluation)							0.8*	0.6	420	19	389	–47	0.8*	

Note: TAW represents the crop Total Available Water (mm), which has been calculated as the difference between soil volumetric moisture at field capacity and wilting point and integrated over the corresponding soil depth. T_{mean} and P_{recip} are mean daily temperature and total precipitation over the experimental season (October–June) of the corresponding trial year, respectively. The gridded datasets aforementioned have been utilized to supply site-specific information on soil and climate. Each observed yield from certain treatment is the average yield over the corresponding number of bread wheat cultivars (in brackets) used in the field trials, and refer to the literature references for specific genotype information. MBE denotes mean bias error between simulations and observations. Slope is the regression coefficient from the linear regression analysis between observed (x) and simulated yields (y). Statistical significance ($p<0.05$) has been denoted with the asterisk, whereas ns means non-significant statistics.

Figure Captions

Fig. 1 Climatic characteristics over the recent-past (1986—2015) period for the Alentejo region in southern Portugal. (**a**) Average annual mean temperature (Tmean, ℃) along with average number of days with maximum temperature (Tmax, ℃) above 30℃ (hot days) during October to December (OND), January to March (JFM) and April to June (AMJ), as well as for (**b**) average annual precipitation (Precip, mm) along with mean climatic water deficit (precipitation minus PET, mm) for the respective three seasonal periods. The white grid in each sub-plot indicates the Alqueva dam.

Fig. 2 Integrated statistical analysis where (**a**) significant correlation coefficient with low error class (MAE≤600 kg/ha and nRMSE≤40%) occurs at identified grid cells when compare actual yield simulations to regional yield statistics over 1986–2015. (**b**) Temporal comparison of spatially averaged (based on the identified grid cells) annual yield simulations under the best-fitted sowing date (Nov_20) with other common practices to regional yield statistics over 1986–2015. The corresponding potential yield simulations in the absence of any abiotic stress (Y_p) are also presented. The asterisk denotes significance at p<0.01.

Fig. 3 Illustrations of simulated seasonal development of mean daily (over 1986–2015) senescent water stress index, photosynthetic Dry Matter Yield (DMY) production rate (kg/ha), grain yield filling rate (kg/ha) and frequency (probability) of daily crop temperature ≥38℃ (heat stress). (**a**) Early sowing date of Oct_30 and (**b**) late sowing date of Dec_20 at three selected representative sites in Alentejo region. The geographic coordinates for the three sites are Beja (37.97°N, 7.96°W), Elvas (38.97°N, 7.21°W) and Evora (38.59°N, 7.96°W).

Fig. 4 Quantified and isolated impacts of main abiotic (drought and heat) stresses on potentially attainable yields over 1986—2015 in Alentejo region without adaptations (simulations are performed under different sowing dates). Quantified mean potential yield losses (%) for individual grids are the average of yearly values (ratio of $Y_w - Y_p$ or $Y_h - Y_p$ to Y_p) over 1986—2015, resulting from either (**a**) seasonal water stress only (**b**) or solely from extreme high temperature (≥38℃) during grain-filling phase.

Fig. 5 Quantified and isolated impacts of main abiotic (drought and heat) stresses on potentially attainable yields over 1986—2015 in Alentejo region with proposed adaptations (simulations are performed under different sowing dates). Quantified mean potential yield losses (%, the same way calculated before) are either only due to (**a**) seasonal water stress but adopting scheduled supplemental irrigation during the sensitive reproductive stage, (**b**) or solely because of the extreme high temperature (≥38℃) during grain-filling phase but introducing the 20% early-flowering/short-cycle cultivar adaptation.

Fig. 6 Simulated average proportion of actual to potential yield over 1986—2015 in Alentejo under combined adaptation options (proposed 20% early-flowering cultivar plus application of supplemental irrigation during the reproductive stage) at different sowing dates.

Fig. 7 Simulations for (**a**) spatial (average yield over 1986–2015) and (**b**) temporal (average yield over the region) wheat yield distributions without and with the combined adaptations (including the climatic potential yield distributions). The individual box-plots from left to right in each defined segment (except for the regional yield statistics) corresponds to sowing date from Oct_30 to Dec_20 with 10 days interval. The box boundaries indicate the 25th and 75th percentiles; the horizontal line within the box marks the median; whiskers below and above the box denote the 10th and 90th percentiles. Note the arithmetic average for both analysed spatial and temporal yield variations would be identical under a given sowing date.