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Supplementary information, figures and tables

This file contains the supplementary material to support the manuscript: *"Local impacts of climate change on winter wheat in Great Britain"*, submitted to the Royal Society Open Science journal.
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We present here the results of additional Sirius simulations.

A. Simulation conditions

The simulations were performed in the following conditions:

- Absence of CO_2 fertilization:
  cultivar: Mercia; sowing date: standard (20 Oct.); soil profile: Hafren (AWC=177 mm); as in the main text;
- Early development cultivar:
  cultivar: Avalon; sowing date: standard (20 Oct.); soil profile: Hafren (AWC=177 mm);
- Reduction of the soil available water content:
  cultivar: Mercia; sowing date: standard (20 Oct.); soil profile: Hanslope (AWC=127 mm);
- Sowing date variations:
  cultivar: Mercia; sowing date: -20 and +20 days than standard; soil profile: Hafren (AWC=177 mm).

The absence of CO_2 fertilization was simulated in Sirius by keeping the atmospheric concentration of CO_2 fixed for the crop at the baseline level of 363.8 ppm, whilst future climates did change due to the increase of CO_2 concentration under the two scenarios RCP4.5 and RCP8.5 exactly as in the main body of this study.

As an alternative cultivar, we used Avalon which is also an obligate winter wheat with moderate to weak daylength response but which is characterised by early development compared to Mercia. The thermal time from anthesis to beginning of grain fill is 50 °C day for Avalon instead of 160 °C day for Mercia.

The soil profile Hanslope was used to estimate the effect of a reduction of the soil water content compared to the Hafren baseline. The Hanslope soil has a lower soil water capacity (AWC) and a smaller percolation coefficient than the Hafren soil (Table. SI. 3). This makes the Hanslope soil less wet and less permeable, which makes water stresses potentially more severe.

Simulations with different sowing dates were also carried out in order to establish whether or not drought and heat stresses around flowering can be avoided by shifting slightly the date of anthesis.

B. Results and comparison

Without CO_2 fertilization, future yield will decrease by about 0.25 t/ha on average compared to baseline, whilst levels of the interannual yield variation (yield CV) and water/drought stresses (WSI95, DSI95) would remain comparable to the levels with CO_2 fertilization (Fig. SI. 3). The mechanisms of CO_2 fertilization, as implemented in Sirius, do not impact the effects of weather variability on the crop response.

Regarding productivity, our simulations show that the productivity increase caused by CO_2 fertilization will also be modest (up to 1.5 t/ha increase on average) for a cultivar with an early development such as Avalon (Fig. SI. 4, Table SI. 4). However, we remark that the choice of a less sensitive cultivar promoted by early development may help mitigate yield instabilities significantly. Sirius simulations predict that, under climate change, the yield CV will drop by about 1% on average and will be distributed more homogenously across the sites with a level remaining close to 8% (Fig. SI. 4(a), Table SI. 4). Rather strikingly, we note that sites in the East of England such as MA could experience a reduction in yield CV reaching 5%, hence leveling off with the rest of the country. The substantial interannual yield variation between locations that we found with a cultivar susceptible to water deficit such as Mercia could then be damped with the choice of a cultivar more tolerant though less productive by about 1 t/ha. This is a consequence of the reduction of yield losses driven by water and drought stresses to levels of about 10% or below by a shift in phenology (Fig. SI. 4(b)).

In contrast, we expect the reverse when the soil available water content is small. Compared to our simulations with the Hafren soil profile, the reduction of AWC by 50 mm in the Hanslope soil decreased yields of the cultivar Mercia by about 1 t/ha on average while its CV rose to 15% for all weather scenarios. The yield losses from water/drought stresses are exacerbated and hit 30% or more, especially in the South East.

To conclude, stable yields can be maintained if given the right choice of cultivar. This is because the earlier or simply different development of the Avalon cultivar enabled it to avoid the water and drought stress that afflicted the Mercia cultivar. Note that early sowing can also contribute to reducing the water/drought stresses (Fig. SI. 6), even in Mercia. The effect of changing the sowing date is diluted by the climate uncertainty in the GCMs, however, suggesting that climate change may render the crop response less sensitive to the time of sowing.

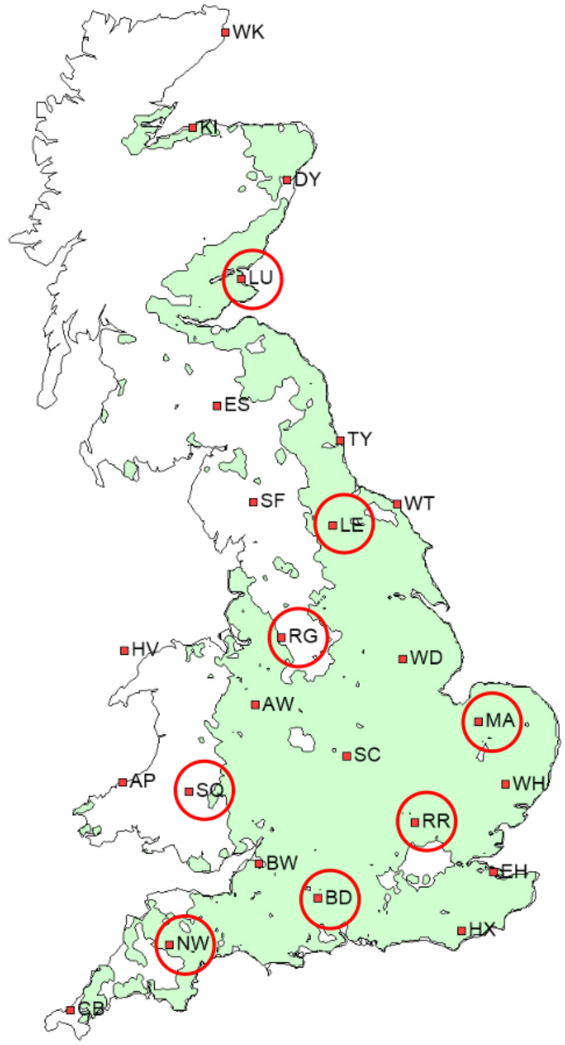


Figure SI 1. Location of the 25 sites. Red circles highlight the 8 specific sites discussed in the study. Geographical coordinates and the definition of the acronyms are listed in Table SI. 2. The green shaded area represents the arable land cover in 2020.

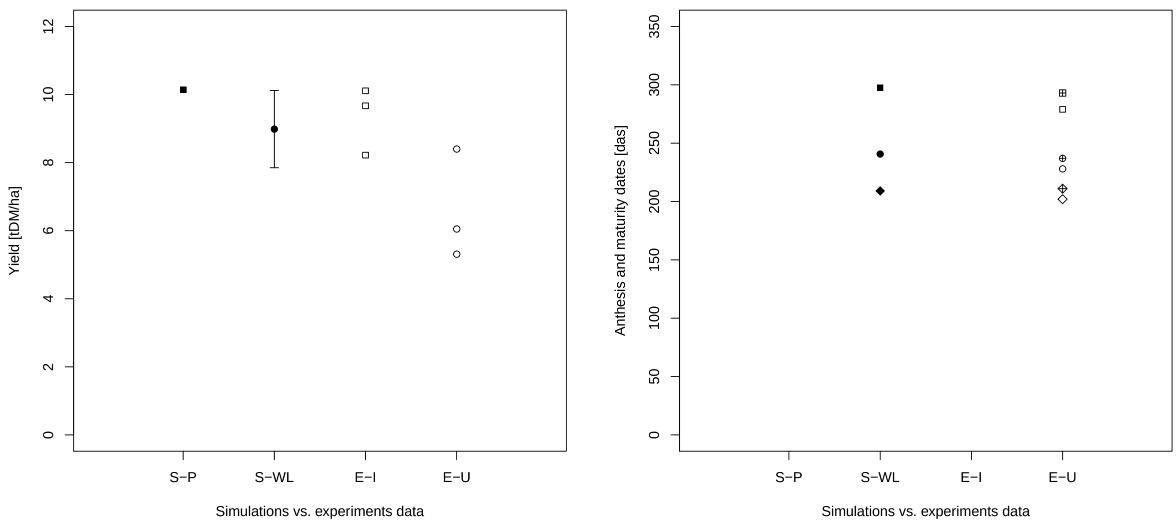
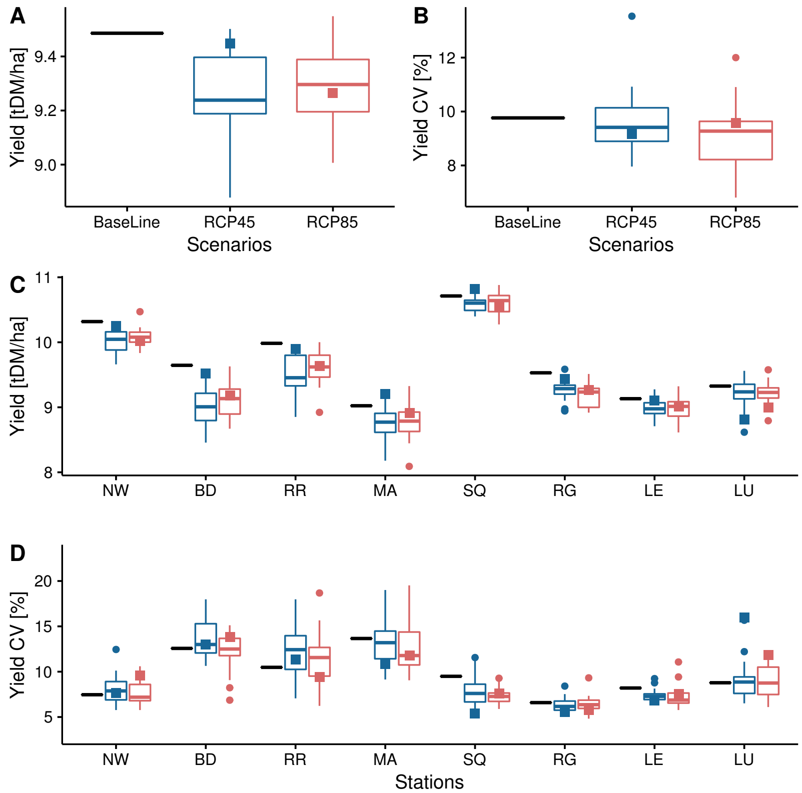
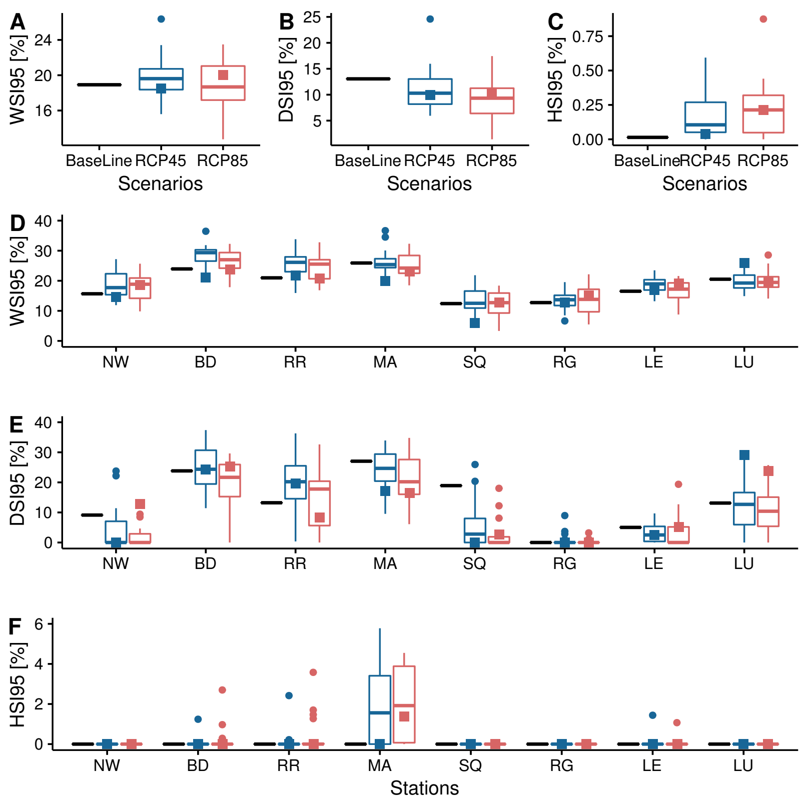


Figure SI 2. Sirius performance for the baseline climate. We present Sirius numerical results (black symbols) for the baseline scenario at the site WD (Waddington) to be compared with experimental results (open symbols) in three dry seasons (1993/94, 1994/95, 1995/96) at ADAS Gleadthorpe reported in [30, 31]. The site WD is chosen due to its geographical proximity to the experimental site; only results for the Mercia cultivar are presented. The left-hand panel shows results for yield: the error bar represents the level of interannual yield variation (SD) caused the interannual weather variability within the 100 years of baseline weather data; the open data points correspond to the three (unirrigated/irrigated) experimental seasons. The right-hand panel shows the flag leaf ligule appearance (diamond), anthesis (circle) and maturity (square) dates (only the years 1994-95 are available). Note that the soil water deficits at flowering and maturity simulated ($\mathrm{SWD}_f = 103.12$ mm, $\mathrm{SWD}_m = 134.34$ mm) are also comparable with the deficits measured in the experiments ($\mathrm{SWD}_f = (75, 116)$ mm, $\mathrm{SWD}_m = (140, 175)$ mm). Nomenclature: Sirius computations: (S-P) no-limitation (potential), (S-WL) water-limited; ADAS experiments: (E-I) irrigated, (E-U) unirrigated.

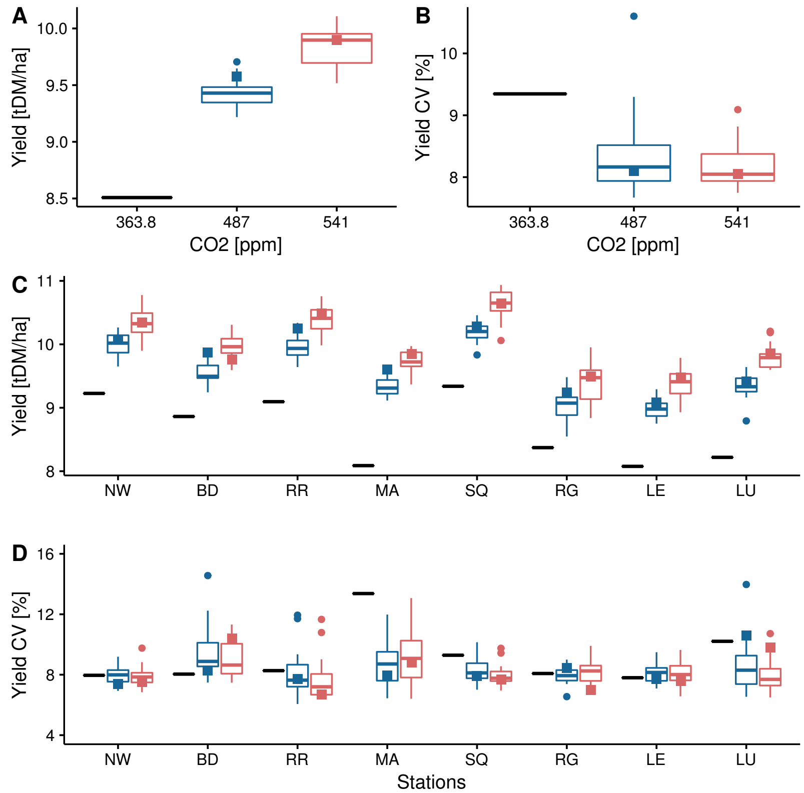


(a) Yield and its coefficient of variation

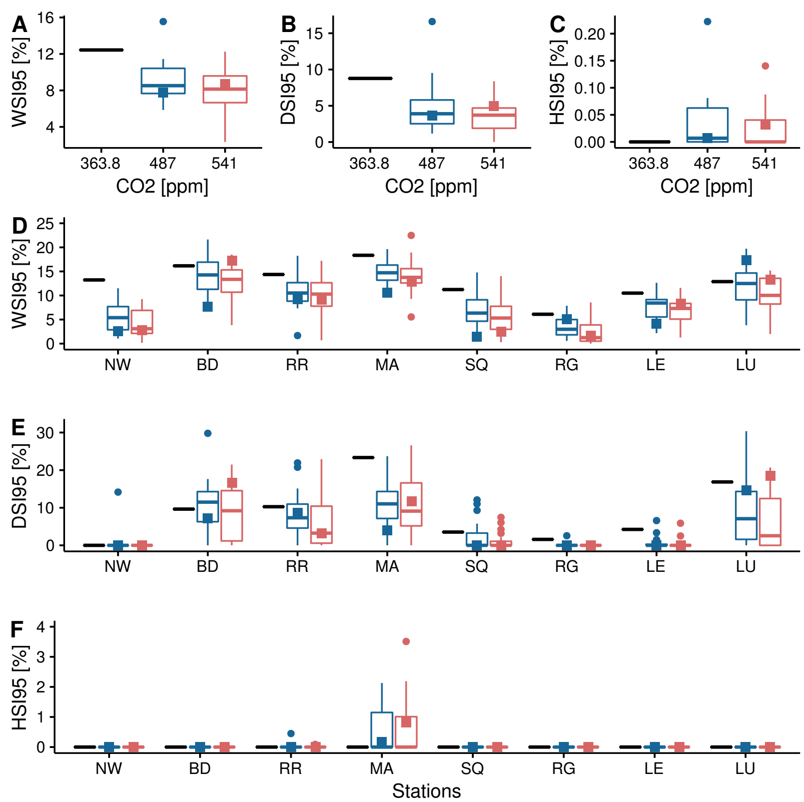


(b) Stresses

Figure SI 3. Absence of CO_2 fertilization. Simulation conditions: cultivar Mercia - Hafren soil (AWC=177). Note a clear but modest yield reduction for the two RCPs.

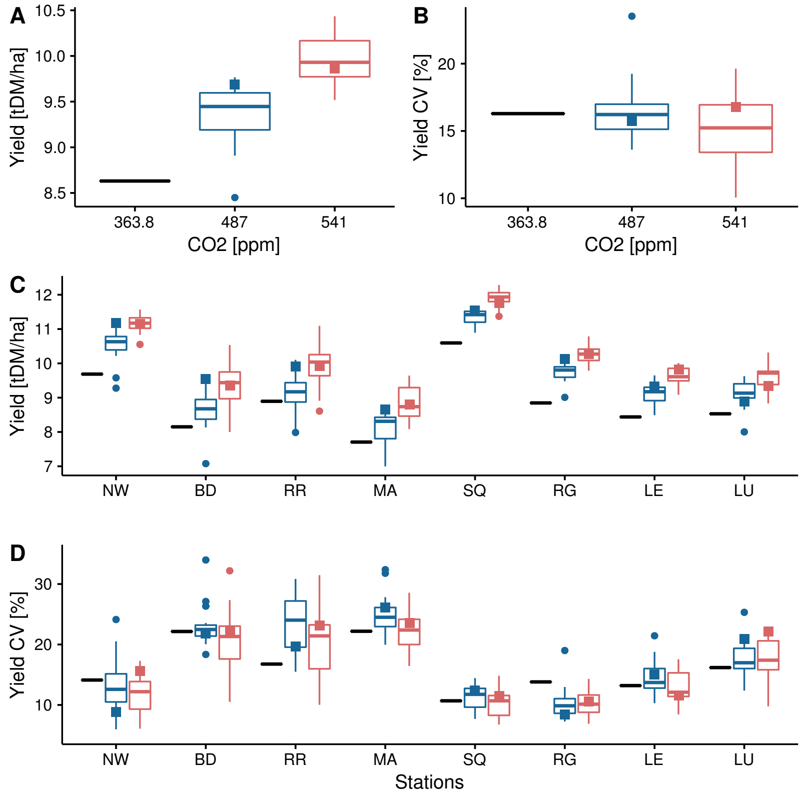


(a) Yield and its coefficient of variation

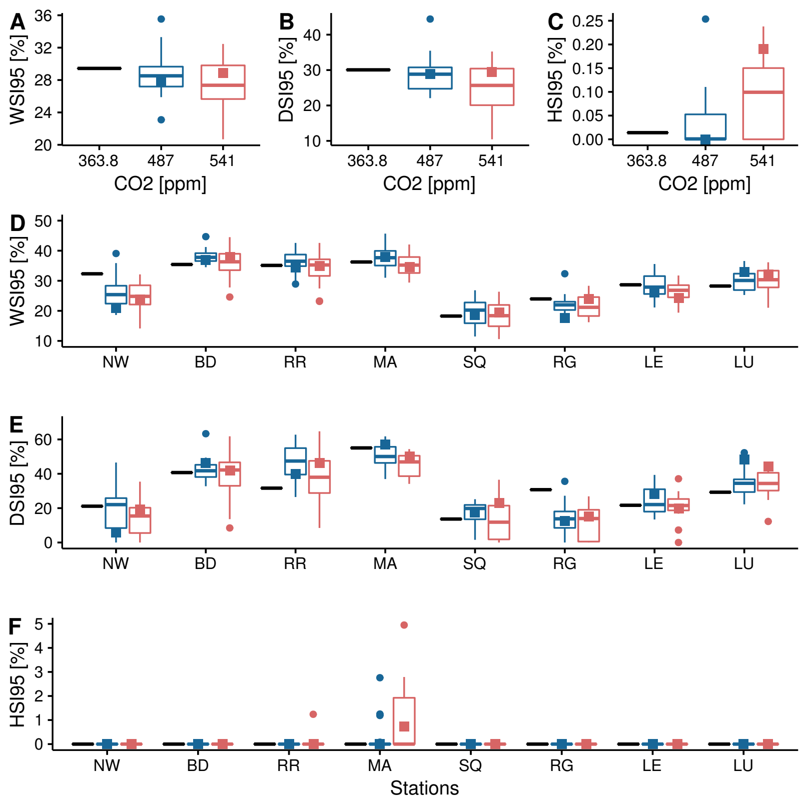


(b) Stresses

Figure SI 4. Effect of the cultivar choice. Simulation conditions: cultivar Avalon - Hafren soil (AWC=177). Avalon is an early development cultivar compared with Mercia HD. Compared to the cultivar Mercia HD, note a reduction of the yield CV, the seasonal water stress (WSI) and the drought stress around flowering (DSI), which suggests that Avalon could ensure more yield stability, despite reduced yields.



(a) Yield and its coefficient of variation



(b) Stresses

Figure SI 5. Effect of a reduction of the soil water capacity. Simulation conditions: Cultivar Mercia HD - Hanslope soil (AWC=127). Note the significant increase of the yield CV, the seasonal water stress (WSI) and the drought stress around flowering (DSI), which indicates high yield instability.

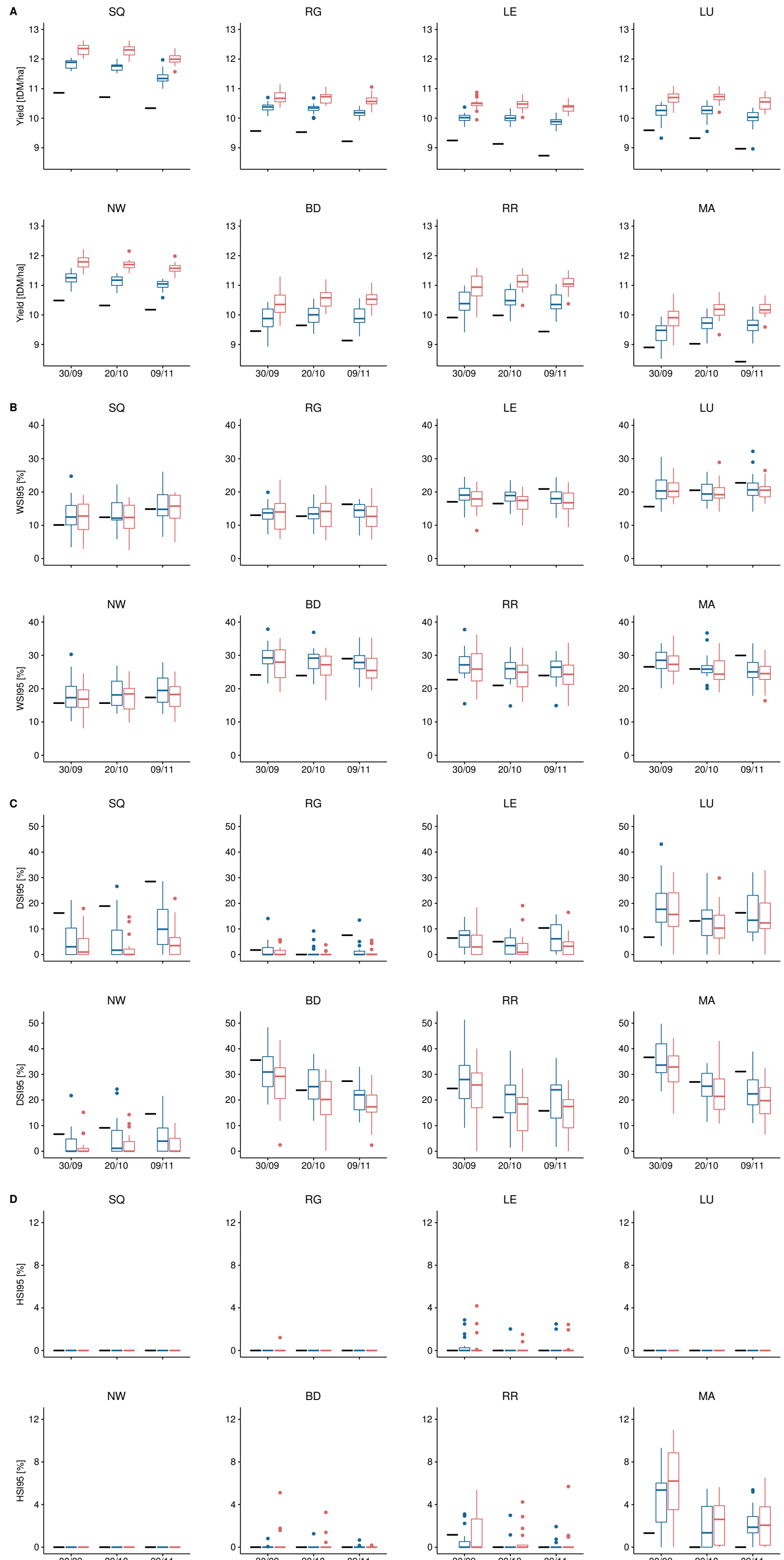


Figure SI 6. Effect of the sowing date. Simulation conditions: cultivar Mercia - Hafren soil (AWC=177). Note that late sowing reduces yields and increases risk; these trends being smoothened with higher levels of atmospheric concentrations.

	Research centre	Country	Model
1	Centre for Australian Weather and Climate Research	Australia	ACCESS1.3
2	Beijing Climate Centre	China	BCC-CSM1.1
3	Canadian Centre for Climate Modelling and Analysis	Canada	CanESM2
4	Centro Euro-Mediterraneo sui Cambiamenti Climatici	Italy	CMCC-CM
5	CNRM-GAME & Cerfacs	France	CNRM-CM5
6	Australia's Commonwealth Scientific and Industrial Research Organisation	Australia	CSIRO-MK36
7	EC-Earth consortium	Europe	EC-EARTH
8	Geophysical Fluid Dynamics Laboratory	USA	GFDL-CM3
9	Goddard Institute for Space Studies	USA	GISS-E2-R-CC
10	UK Meteorological Office	UK	HadGEM2-ES
11	Institute for Numerical Mathematics	Russia	INM-CM4
12	Institut Pierre Simon Laplace	France	IPSL-CM5A-MR
13	University of Tokyo, National Institute for Environmental Studies Japan Agency for Marine-Earth Science & Technology	Japan	MIROC5
14	University of Tokyo, National Institute for Environmental Studies Japan Agency for Marine-Earth Science & Technology	Japan	MIROC-ESM
15	Max Planck Institute for Meteorology	Germany	MPI-ESM-MR
16	Meteorological Research Institute	Japan	MRI-CGCM3
17	National Center for Atmospheric Research	USA	NCAR-CCSM4
18	National Center for Atmospheric Researc	USA	NCAR-CESM1-CAM5
19	Norwegian Climate Centre	Norway	NorESM1-M

Table SI 1. Global climate models (GCMs). List of the 19 GCMs from the CMIP5 ensemble incorporated in the LARS-WG weather generator. Scenarios are available for RCP4.5 and RCP8.5 Representative Concentration Pathways and based on 20 yr periods between 2010 and 2100. See [23, 44] for more details.

Site	Acronym	Lat. [°]	Lon. [°]	Alt. [m]
Aberporth	AP	52.14	-4.57	133.00
Shawbury	AW	52.79	-2.66	72.00
Boscombe Down	BD	51.16	-1.75	126.00
Bristol Weather Centre	BW	51.45	-2.60	42.00
Camborne	CB	50.22	-5.33	87.00
Dyce	DY	57.21	-2.20	65.00
East Hamsted	EH	51.38	0.78	75.00
Eskdalemuir	ES	55.31	-3.21	242.00
Holyhead Valley	HV	53.25	-4.54	10.00
Herstmonceux	HX	50.89	0.32	52.00
Kinloss	KI	57.65	-3.56	5.00
Leeming	LE	54.30	-1.53	32.00
Leuchars	LU	56.38	-2.86	10.00
Marham	MA	52.65	0.57	21.00
North Wykes	NW	50.77	-3.90	177.00
Ringway	RG	53.36	-2.28	33.00
Rothamsted Research	RR	51.80	-0.35	128.00
Saws Church Lawford	SC	52.36	-1.33	107.00
Saws Shap Fell	SF	54.50	-2.68	255.00
Saws Sennybridge	SQ	52.06	-3.61	307.00
Tynemouth	TY	55.02	-1.42	33.00
Waddington	WD	53.18	-0.52	68.00
Wattisham	WH	52.12	0.96	89.00
Wick	WK	58.45	-3.09	36.00
Whitby	WT	54.48	-0.60	41.00

Table SI 2. Geographical locations of the 25 sites.

Type	Depth [m]	AWC [mm]	Kq	Layers
Hafren	1.35	177	0.95	27
Hanslope	1.20	127	0.3	24

Table SI 3. Soil parameters. AWC: available water content; Kq: percolation coefficient.

Simulations conditions	Yield		Stress indices	
	Baseline	2050	Baseline	2050
Absence of CO_2 fertilization		○ modest reduction of yield about 0.25 t/ha less		
Cultivar	○ yield reduction about 1 t/ha less ○ slight reduction of the yield CV, whose level (about 8 %) more homogeneous across stations (except MA)	○ reduction of the yield CV to a level of 8 %	○ reduction of WSI95 and DSI95 by a few percents	○ significant reduction of WSI95 and DSI95 below 10 %
AWC reduction	○ yield reduction about 1 t/ha less ○ significant increase of the CV reaching 15 %	○ similar trends however consistent with baseline (i.e. smaller yields with larger CV)	○ large increase of WSI95 and DSI95 about 100 %	○ similar trends but larger values consistent with baseline ○ slight reduction of HSI95
Sowing dates	○ slight reduction of yield associated with late sowing	○ yield variations between sowing dates damped	○ increase of WSI95 and DSI95 associated with late sowing (apart for northern sites)	○ differences between sowing dates are smoothened

Table SI 4. Effects of simulations conditions. We highlight the main effects (on average) of changing simulations conditions, taking as reference the results for the cultivar Mercia HD with the Hafren soil profile (AWC=177). Empty cells mean that no significant difference is observed.