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Green water availability and water-limited crop yields under a changing climate in Ethiopia

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Table S1: List of the administrative zones within the nine regional states of Ethiopia based on pre-2010 divisions. The short names are arbitrary designations used in Fig. 1.

Short name	Long name	Region
NWT	North West Tigray	Tigray
CTI	Central Tigray	
ETI	Eastern Tigray	
STI	Southern Tigray	
WTI	Western Tigray	
ZO1	Zone 1	Afar
ZO2	Zone 2	
ZO3	Zone 3	
ZO4	Zone 4	
ZO5	Zone 5	
NGO	North Gondar	Amhara
SGO	South Gondar	
NWO	North Wello	
SWO	South Wello	
aNSH	North Shewa	
EGO	East Gojam	
WGO	West Gojam	
WAG	Wag Himra	
AWI	Awi	
ORO	Oromia	
WWL	West Wellega	Oromia
EWL	East Wellega	
ILU	Ilu Aba Bora	
JIM	Jimma	
WSH	West Shewa	
oNSH	North Shewa	
ESH	East Shewa	
ARS	Arsi	
WHA	West Hararge	
EHA	East Hararge	
BAL	Bale	
BOR	Borena	
SWS	South West Shewa	
GUJ	Guji	
wARS	West Arsi	

Short name	Long name	Region
SHI	Shinile	Somali
FAF	Fafan	
LIB	Liben	
AFD	Afder	
DOL	Dolo	
JAR	Jarar	
SHB	Shabelle	
KOR	Korahe	
SIT	Siti	
NOG	Nogob	
MET	Metekel	Benishangul-gumz
ASO	Asosa	
KEM	Kemashi	
GUR	Gurage	SNNPR
HAD	Hadiya	
KET	Kembata Tibaro	
KEF	Kefa	
GGO	Gamo Gofa	
BMJ	Bench Maji	
YEM	Yem Special	
AMA	Amaro Special	
BUR	Burji Special	
KONs	Konso Speicial	
DER	Derashe Special	
DAW	Dawuro	
BAS	Basketo Special	
KON	Konta Special	
SIL	Siltie	
ALB	Alaba Special	
ALL	Alle	
WOL	Wolaita	
SOM	South Omo	
SID	Sidama	Sidama
AGN	Agnuak	Gambela
MAJ	Majang	
NUE	Nuer	

Table S2: List of the CMIP6 model projections used for the projection of the precipitation, maximum and minimum temperature and incoming shortwave radiation over Ethiopia. The 'x' marks show the variables that were used from the indicated model.

Model	Institution (country/region)[1]	Precip	Tmax	Tmin	Rsw	Reference
ACCESS-CM2	CSIRO (Australia)	x	x	x	x	(Bi et al., 2020)
AWI-CM-1-1-MR	AWI (Germany)	x	x	x	x	(Semmler et al., 2020)
BCC-CSM2-MR	BCC (Asia)	x			x	(Wu et al., 2019)
CAMS-CSM1-0	CAMS (China)	x			x	(Rong et al., 2019)
CanESM5-CanOE	CCCma (Canada)	x	x	x	x	(Christian et al., 2022)
CESM2	NCAR (USA)	x			x	(Danabasoglu et al., 2020)
CIESM	THU (China)		x	x		(Lin et al., 2020)
CMCC-CM2-SR5	CMCC (Italy)	x			x	(Cherchi et al., 2019)
CMCC-ESM2		x	x	x	x	(Lovato et al., 2022)
CNRM-CM6-1	CNRM (France)	x	x	x	x	(Voldoire et al., 2019)
CNRM-CM6-1-HR		x	x	x	x	
CNRM-ESM2-1		x	x	x	x	
EC-Earth3-Veg-LR	EC-Earth (Europe)		x	x		(Döscher et al., 2022)
FGOALS-g3	CAS (China)	x	x	x	x	(Li et al., 2020)
FIO-ESM-2-0	FIO-QNLM (China)	x	x	x	x	(Bao et al., 2020)
GFDL-ESM4	NOAA-GFDL (USA)	x	x	x	x	(Dunne et al., 2020)
HadGEM3-GC31-LL	MOHC (UK)	x	x	x	x	(Andrews et al., 2020)
IITM-ESM	CCCR-IITM (India)	x	x	x	x	(David A. et al., 2019)
INM-CM4-8	INM (Russia)		x	x		(Volodin et al., 2018)
INM-CM5-0		x	x	x	x	
IPSL-CM6A-LR	IPSL (France)	x	x	x	x	(Boucher et al., 2020)
MIROC6	MIROC (Japan)	x	x	x	x	(Tatebe et al., 2019)
MIROC-ES2L		x	x	x	x	(Hajima et al., 2020)
MPI-ESM1-2-LR	MPI (Germany)	x	x	x	x	(Gutjahr et al., 2019)
NESM3	NUIST (China)	x			x	(Cao et al., 2018)
NorESM2-MM	NCC (Norway)	x			x	(Seland et al., 2020)
TaiESM1	AS-RCEC (Taiwan)	x			x	(Wang et al., 2021)
UKESM1-0-LL	MOHC (UK)	x	x	x	x	(Sellar et al., 2019)

[1] The full names of the institutions can be found in (IPCC, 2021)

Table S3: List of the 20 surface runoff measurement sites and measurement periods collected from published literature for the validation of the simulated surface runoff.

Measurement site	Lat (° N)	Lon (° E)	Measurement periods (Values used in the evaluation)	Reference
Maybar	11.02	39.67	1982-1993 (mean)	(Herweg and Stillhardt, 1999) (Herweg and Ludi, 1999)
Hunde lafto	9.07	41.00	1983-1993 (mean)	
Andit Tid	9.80	39.72	1982-1992 (mean)	
Gununo	6.92	37.65	1985-1993 (mean)	
Anjeni	10.81	37.57	1985-1993 (annual)	
Dendi	9.13	37.12	2007-2009 (annual)	(Adimassu et al., 2014)
Holeta	9.07	38.48	2009-2010 (annual)	(Adimassu et al., 2019)
Debre Mawi	11.33	37.43	2008-2009 (annual)	(Amare et al., 2014)
Chefe donsa	8.96	39.11	2001-2002 (annual)	(Erkossa et al., 2006)
Dera	8.36	39.34	2004 (annual)	(Welderufael et al., 2008)
Yeku	12.52	39.07	2003 (annual)	(Collick et al., 2009)
Guder*	8.95	37.75	2003 (annual)	(Tumsa et al., 2022)
Dodota*	11.50	39.92	1994-2000 (mean)	(Teso et al., 2010)
Keleta	8.12	39.46	1981, 1990 (annual)	(Tibebe and Bewket, 2011)
Suluh*	13.80	39.50	1992-2003 (mean)	(Abebe, 2014)
Hare*	6.25	37.55	1990-1999 (mean)	(Wagesho et al., 2013)
Bilate*	7.50	37.94	1990-1999 (mean)	
Hagere Selam	13.65	39.17	2003-2004 (annual)	(Descheemaeker et al., 2006)
Adigudem	13.233	39.53	2005-2007 (annual)	(Araya et al., 2011)
Jigjiga	9.47	42.63	2004-2005 (annual)	(Welle et al., 2006)

*These are model-calibrated surface runoff data: Guder (SWAT+), Dodota (SWAT), Suluh (HEC-HMS), Hare and Bilate (SWAT)

Table S4: List of the case study sites and Global Yield Gap Atlas (GYGA) stations at which the water-limited attainable yield (AY) were compared with the measured (field trials), crop model-simulated, or GYGA-derived ratio of water-limited (Yw) and potential (Yp) yields. The data from the field trials and model simulations correspond to various crops including maize, sorghum, wheat, rice, soya bean, faba bean, and chickpea. The GYGA data were collected for maize.

Experimental site	Lat (° N)	Lon (° E)	Crop	Years of experiment	Reference
Hawassa, Sidama	7.028	38.482	Wheat	2009	(Kassie et al., 2014)
Ziway (Batu), East Shoa	7.882	38.714	Wheat	2004	
Sinana, Bale**	7.117	40.167	Maize	2014-2015	(Dinsa and Bogale, 2023)
Kersa, Jimma*	7.750	37.080	Soya bean	1987-2019	(Mekonnen et al., 2022)
Limu Seka, Jimma*	7.595	36.723		1987-2019	
Omonada, Jimma*	7.599	37.250		1987-2019	
Tiro Afeta, Jimma*	7.854	37.238		1987-2019	
Bishoftu, East Shoa	8.765	39.005	Wheat	1987-1988	(Astatke et al., 1991)
Sekota, Waghimra**	12.680	39.010	Sorghum	2014-2015	(Wale et al., 2019)
Fogera, South Gondar**	11.833	37.628	Rice	2015-2016	(Molla et al., 2021)
Mekele, East Tigray**	13.483	39.583	Wheat	2012	(Girmay, 2017)
Sirinka, North Wollo**	12.080	39.280	Sorghum	2011-2012	(Wondatir and Getnet, 2021)
Gondar, North Gondar**	12.467	37.483	Chickpea	2015-2016	(Kemal et al., 2019)
Halaba, Alaba Woreda**	7.283	37.010	Maize	2012-2013	(Muluneh et al., 2017)
Debre Tabor, South Gondar*	11.850	38.017	Faba bean	2000-2009	(Mulugeta et al., 2019)
Bekoji, Arsi*	7.544	39.256			
Meraro, Arsi*	7.408	39.249			
Arsi-Robe, Arsi*	7.884	39.628			
Gasera, Bale*	7.367	40.300			
Adadi, Southwest Shoa*	8.633	38.013			
Kofle, West Arsi*	7.074	38.795			
Bulle, Gedio*	6.300	38.417			
Hosena, Hadiya*	7.568	37.856			
Angacha, Kembata-tembaro*	7.333	37.850			
Kokate, Wolayita*	6.822	37.749			
Adet, West Gojjam	11.27	37.48	Maize	2001-2010	www.yieldgap.org
Ambo, West Shoa	8.96	37.835			
Arbaminch, Gamo Gofa	6.05	37.4			
Areka, Wolayita	7.04	37.45			
Assosa, Assosa	10.07	34.52			
Ayira, Kelem Wollega	9.06	35.33			
Bahir Dar, Bahir Dar	11.58	37.38			
Bako, West Shoa	9.07	37.03			
Butajira, Gurage	8.08	38.22			
Debre Markos, East Gojjam	10.33	37.736			
Gore, Illubabor	8.02	35.53			

Haramaya, East Hararge	9.4	42.03			
Harar, East Hararge	9.31	42.1			
Jimma, Jimma	7.84	36.43			
Kulumsa, Arsi	8	39.15			
Melkassa, East Shoa	8.4	39.33			
Nekemte, East Wollega	9.09	36.54			
Pawe, Metekel	11.31	36.403			
Shambu, Horro Guduru Wollega	9.57117	37.1212			
Shire Endasilasse, Northwestern Tigray	14.1	38.334			
Woliso, Southwest Shoa	8.55	37.97			
Wolkite, Gurage	8.27	37.78			

*These are model-simulated data

** The measurement periods fall outside the reference period (1981-2010) of this study. However, these data remain valuable for evaluating the simulated results. These were compared to the average simulated AY for the later years (2007-2010), while all others were compared with the average for the specific years of the experiments indicated in the table.

Table S5: Published potential (fully irrigated, optimally fertilized) maize yields measured at 14 experimental sites across the RFA region of Ethiopia, used for the analysis of yield gaps.

Experimental site	Potential yield, Yp (ton/ha)	Lat (° N)	Lon (° E)	Reference
Salaklaka, Northwest Tigray	7.3	14.3	38.72	(Gebreigziabher, 2020)
Melkasa, East Shoa	7.9	8.4	39.35	(Seid, Mulugeta M; Narayanan, 2015)
Boloso Sore, Wolayta	8.8	7.0	37.75	(Chinasho et al., 2023)
Tepi, SW Ethiopia	6.8	7.187	35.42	(Zeleke, 2020)
Raya, South Tigray	8.7	12.7	39.7	(Mehari et al., 2020)
Arba Minch, Gamo Gofa	8.0	6.08	37.58	(Setu et al., 2023)
Koga, West Gojam	5.9	11.37	37.12	(Abiyu and Alamirew, 2015)
Haru ARC, West Wollega	8.4	8.90	35.87	(Admasu et al., 2017)
Adami Tulu, East Shoa	4.5	7.75	38.65	(Furgassa, 2017)
Mehoni, South Tigray	5.7	12.87	39.64	(Mebrahtu and Mehamed, 2019)
Haramaya, East Hararge	7.1	9.417	42.04	(Mengiste and Tilahun, 2009)
Hawassa, Sidama	9.0	7	38	(Jemal and Berhanu, 2020)
Koka, East Shoa	6.3	8.43	39	(Meskelu et al., 2018)
Gumselasa, South Tigray	9.9	13.25	39.51	(Mintesinot et al., 2004)

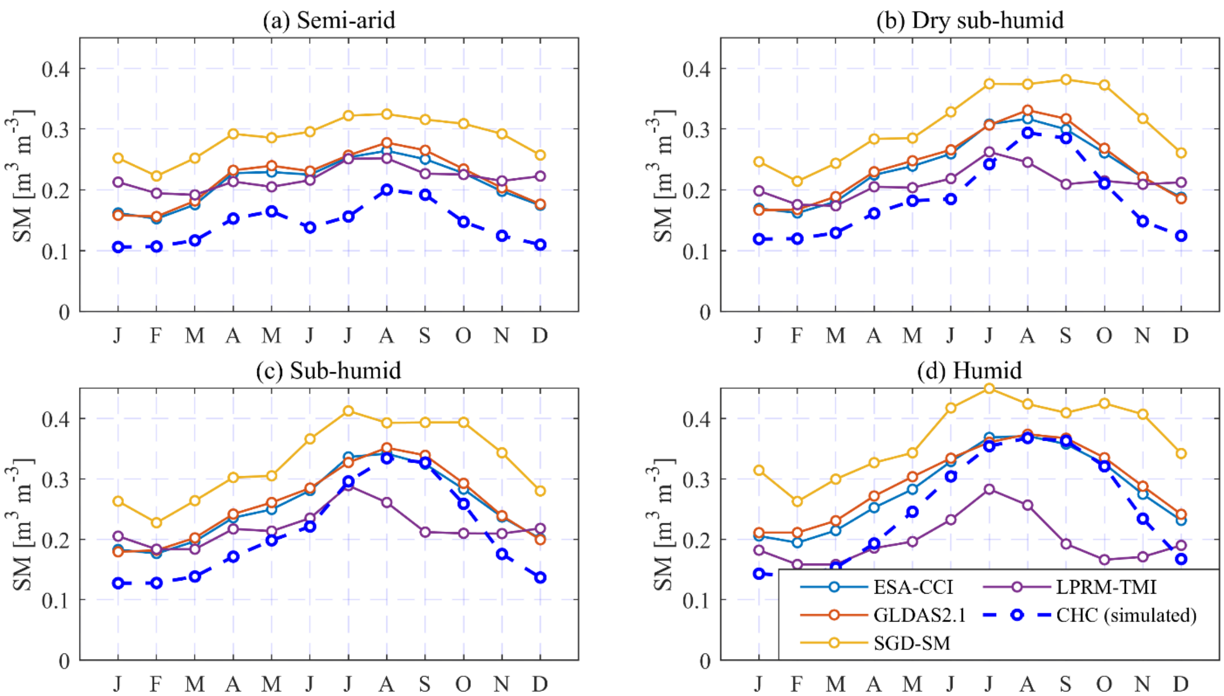

Figure S1 Comparison of area-averaged annual cycles of the simulated and satellite and model-based global soil moisture (SM) datasets across the four climatic regimes (see Figure 1c in the main article) for the record period 2003-2010.

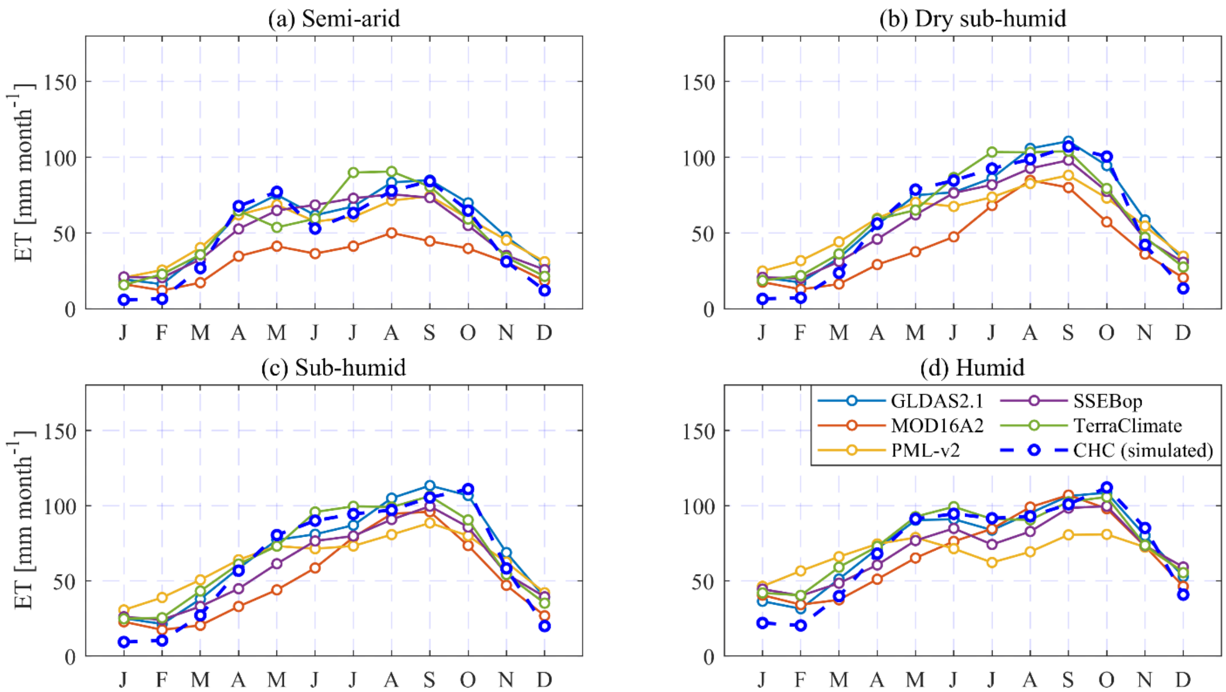

Figure S2: Comparison of area-averaged annual cycles of the simulated and satellite and model-based global actual evapotranspiration (ETa) datasets across the four climatic regimes (see Figure 1c in the main article) for the record period 2003-2010.

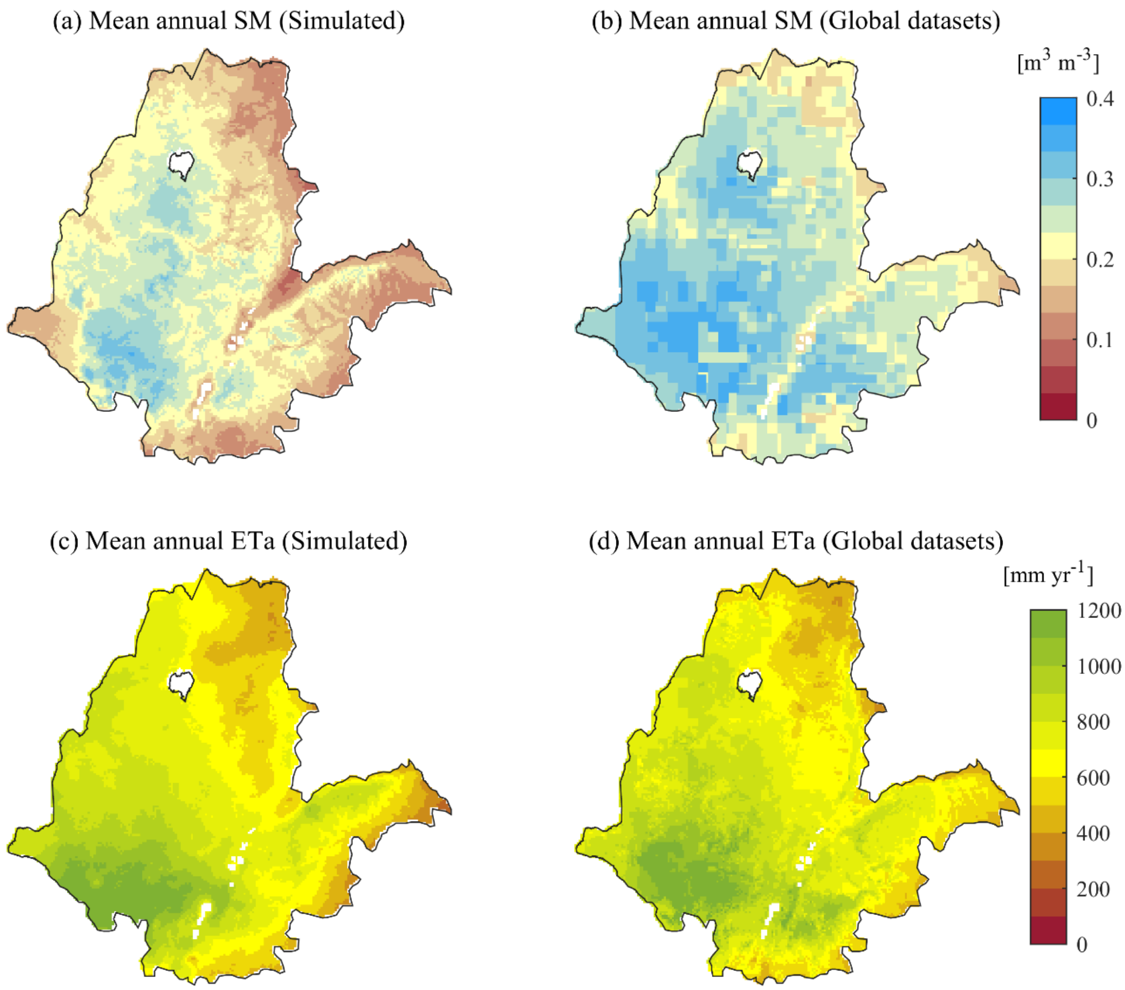

Figure S3: Maps of simulated and global mean annual SM (a and b), and ETa (c and d) for the record period 2003-2010. The mean global SM data mapped here is the median of four SM products (ESA CCI, GLDAS2.1, LPRM-TMI, and SGD-SM). The mean global ETa is the median of five ETa products (GLDAS2.1, MOD16A2, PML-v2, SSEBop, and TerraClimate)

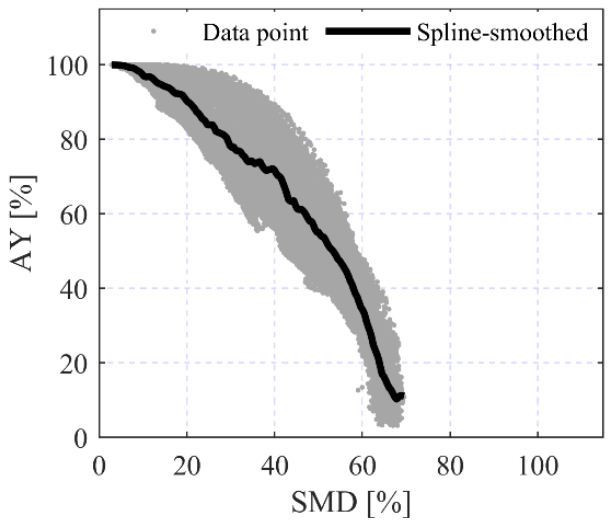

Figure S4: The relationship between AY and SMD in the RFA region of Ethiopia. Each data point represents a single grid cell in the RFA domain considering both Meher and Belg growing seasons.

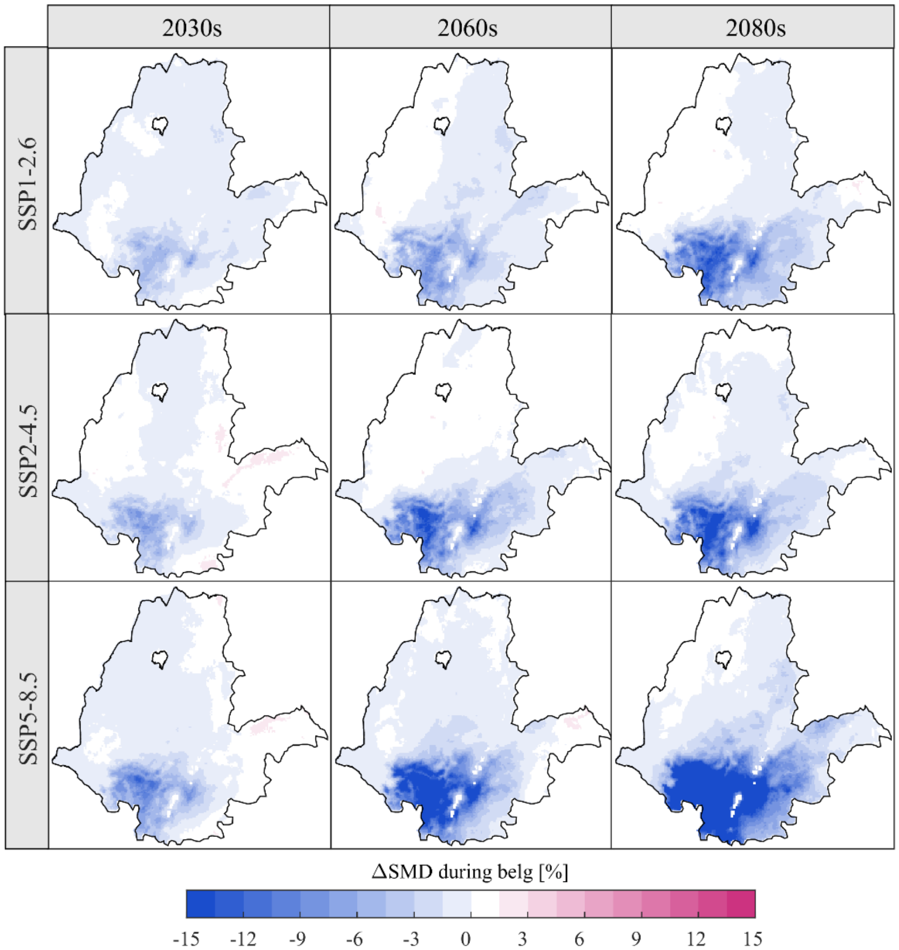

Figure S5: Projected changes in soil moisture deficit (SMD) across the rainfed agricultural region of Ethiopia during the Belg growing season under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios in the 2030s, 2060s, and 2080s

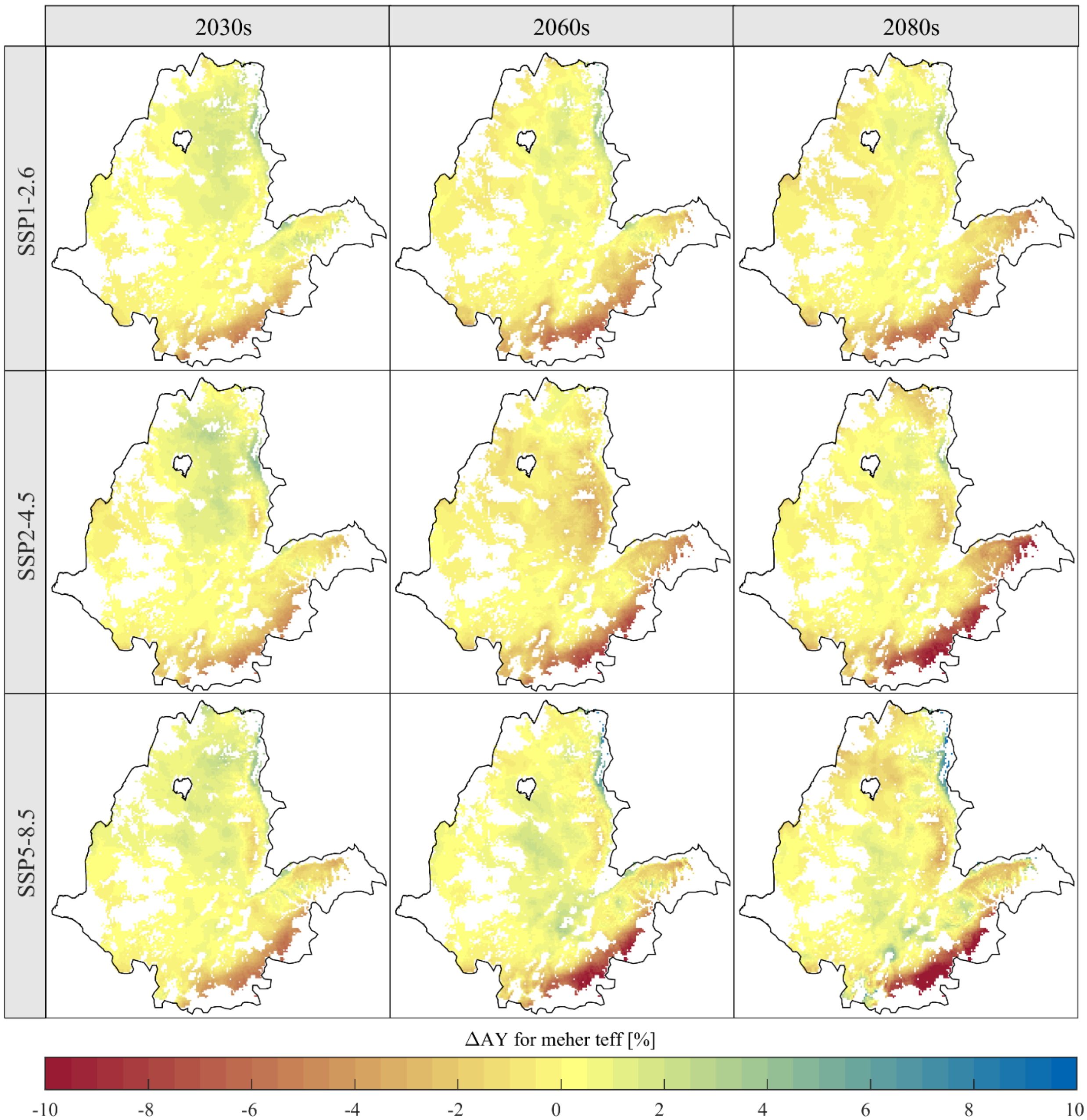

Figure S6: Projected changes in Meher water-limited attainable yield (AY) for teff under the SSP1-2.6, SSP2-4.5, and SSP5-8.5. The RFA region was masked using cropland suitability maps (Wakjira et al., under review) to restrict the analysis to areas potentially suitable for each crop. The non-producing areas during both seasons were also masked out following the Atlas of Ethiopian Rural Socioeconomy (IFPRI and CSA, 2006).

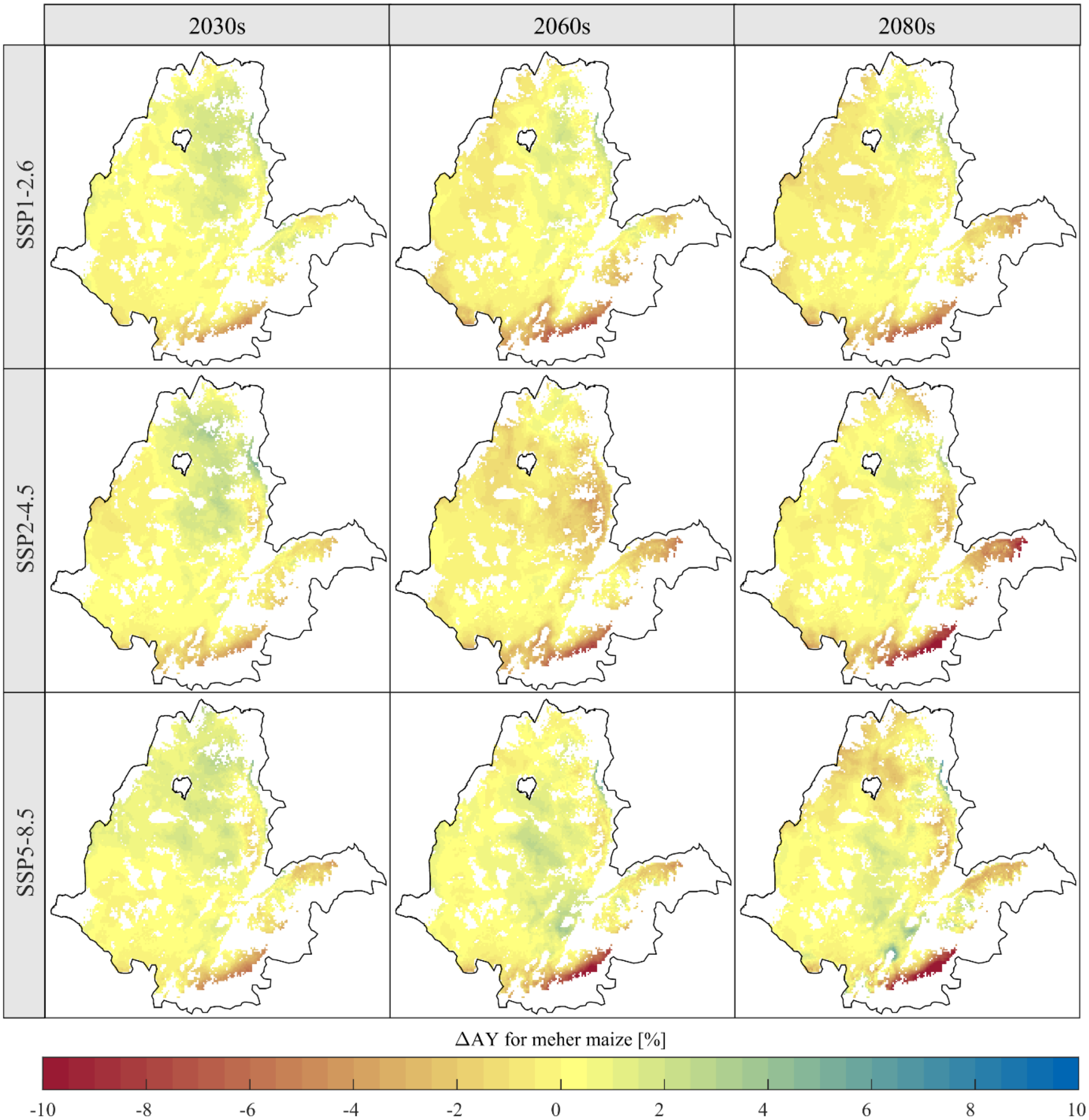

Figure S7: The same as Figure S6, but for maize

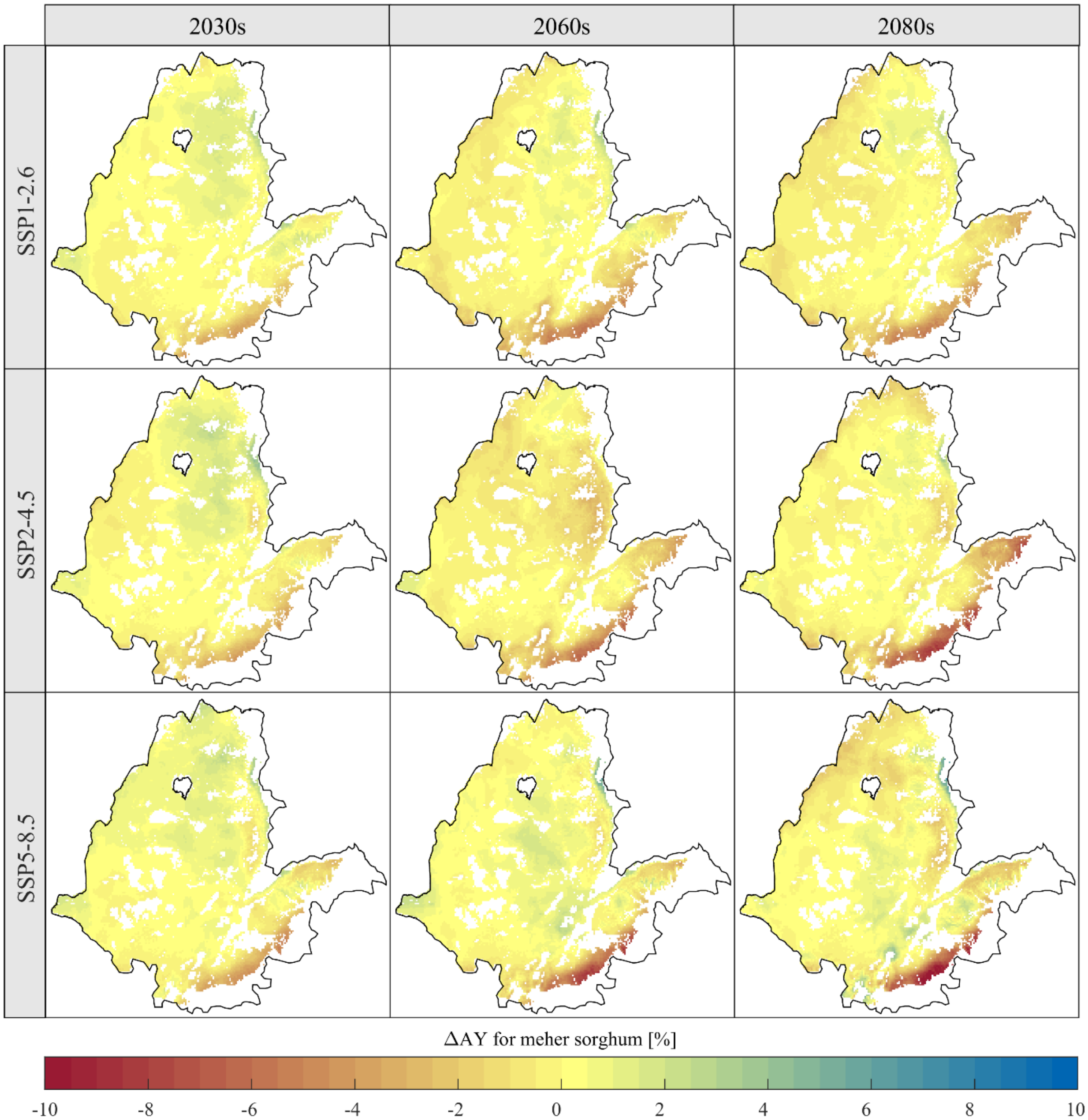

Figure S8: The same as Figure S6, but for sorghum

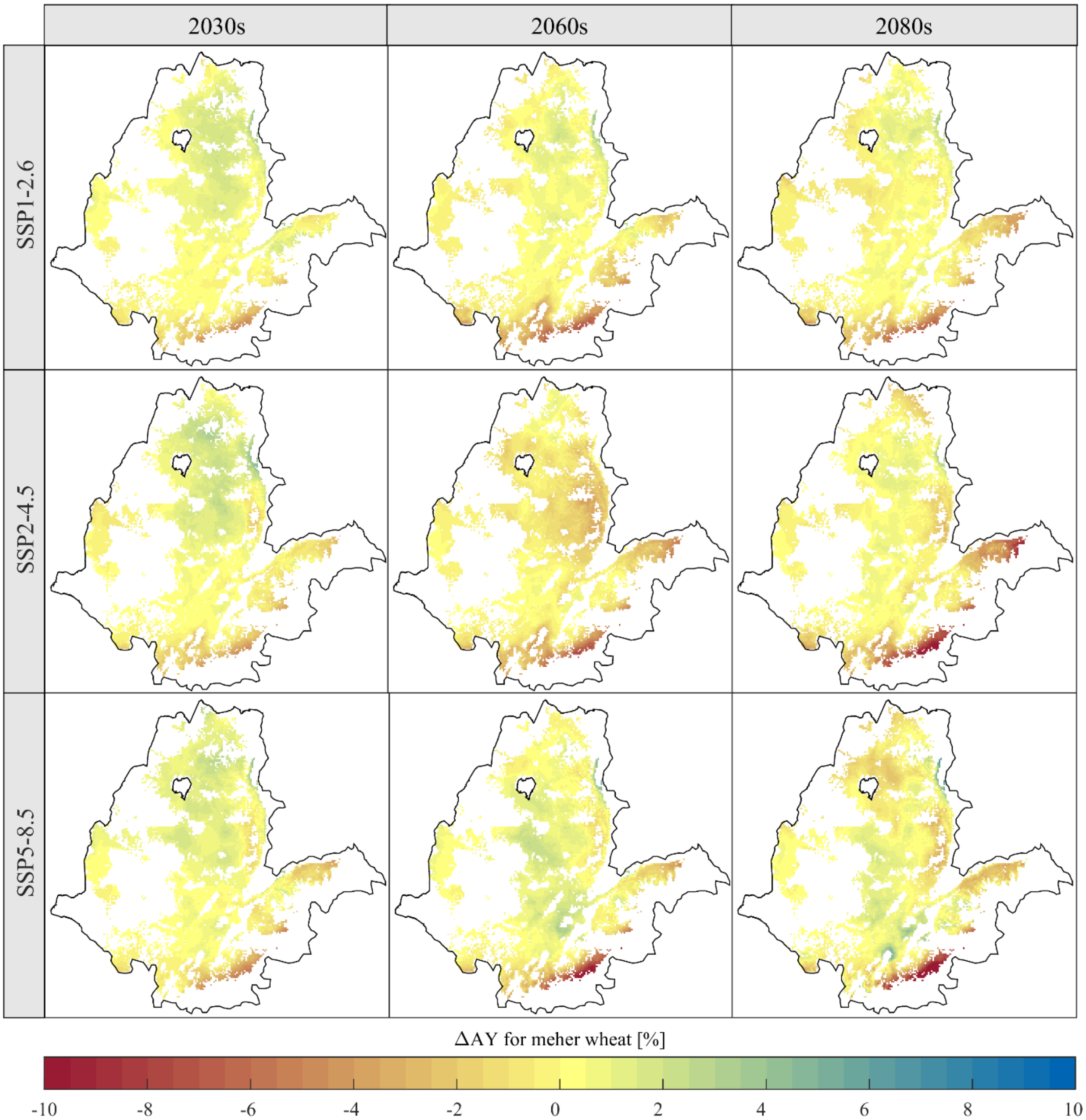

Figure S9: The same as Figure S6, but for wheat

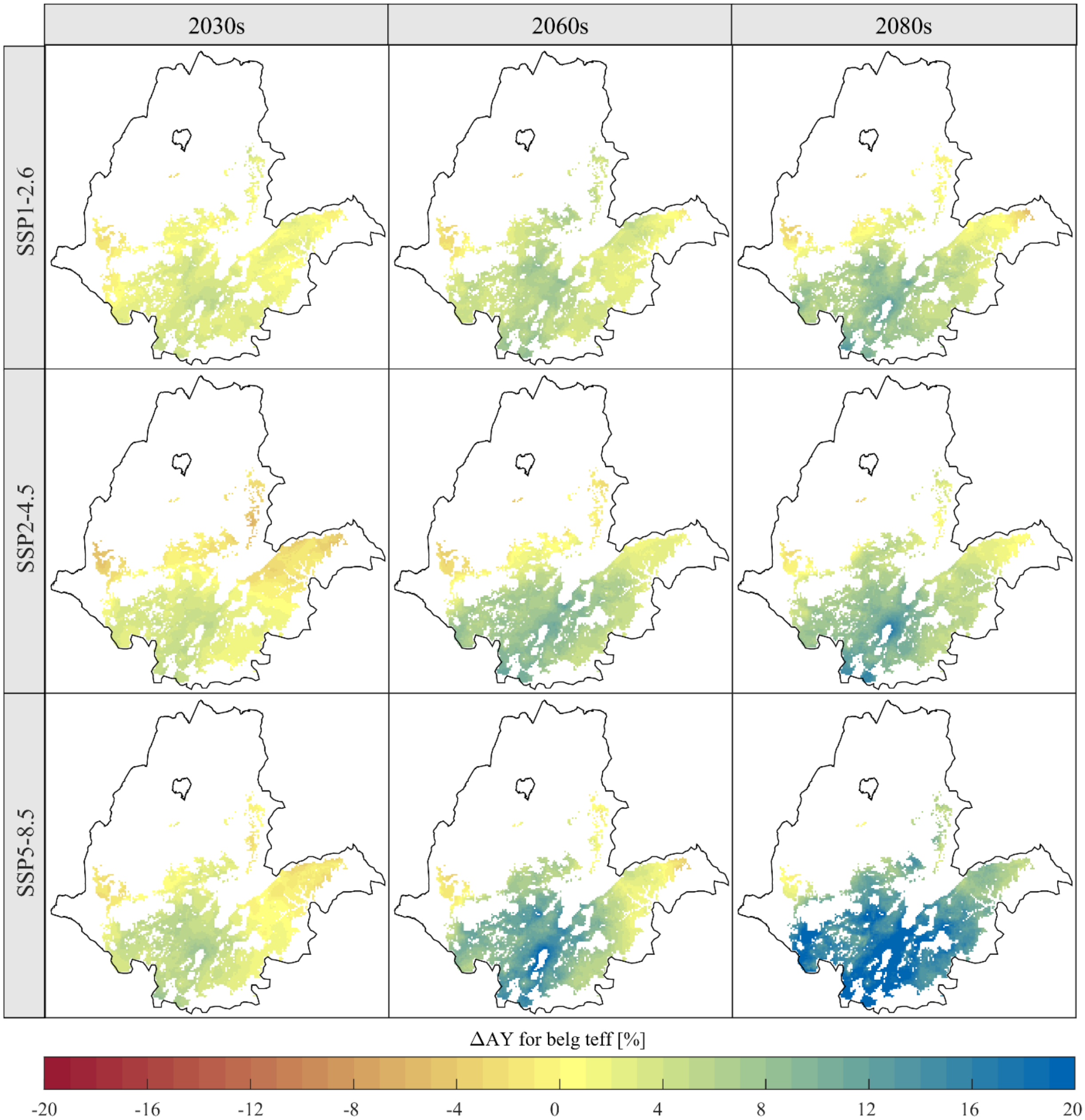

Figure S10: Projected changes in Belg water-limited attainable yield (AY) for teff under the SSP1-2.6, SSP2-4.5, and SSP5-8.5. The RFA region was masked using cropland suitability maps (Wakjira, 2024) to restrict the analysis to areas potentially suitable for each crop. The non-producing areas during both seasons were also masked out following the Atlas of Ethiopian Rural Socioeconomy (IFPRI and CSA, 2006).

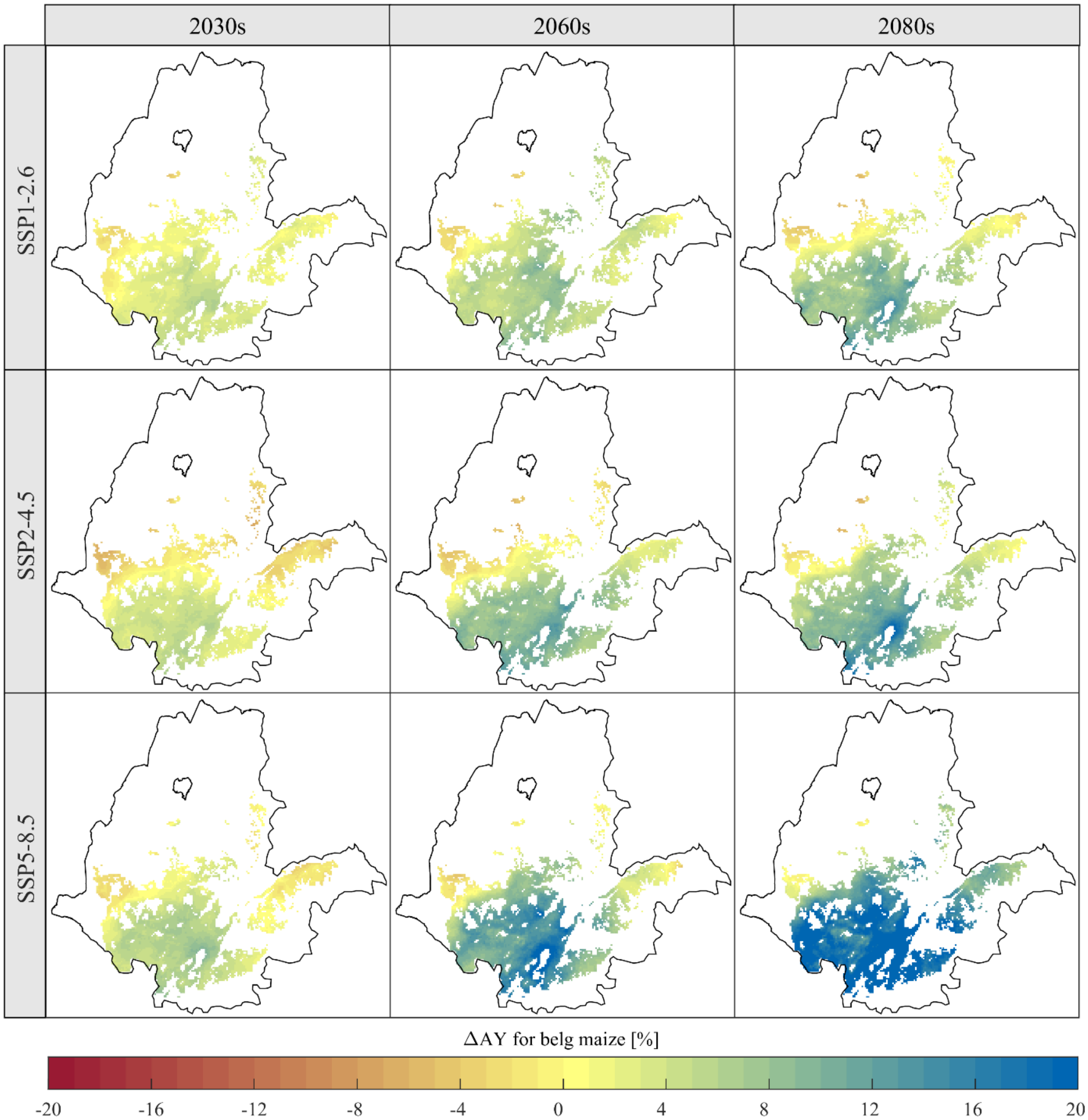

Figure S11: The same as Figure S10, but for maize

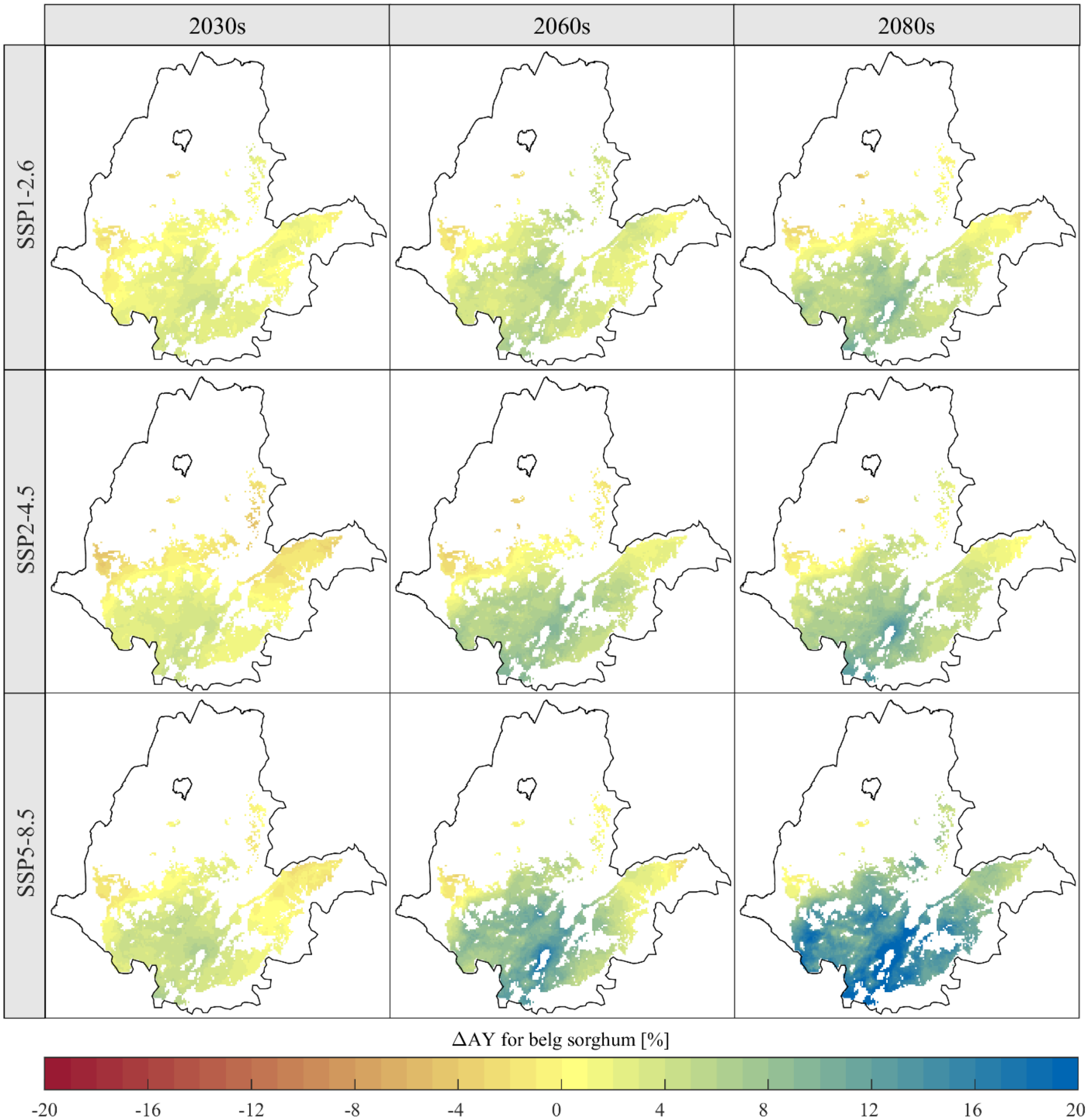

Figure S12: The same as Figure S10, but for sorghum

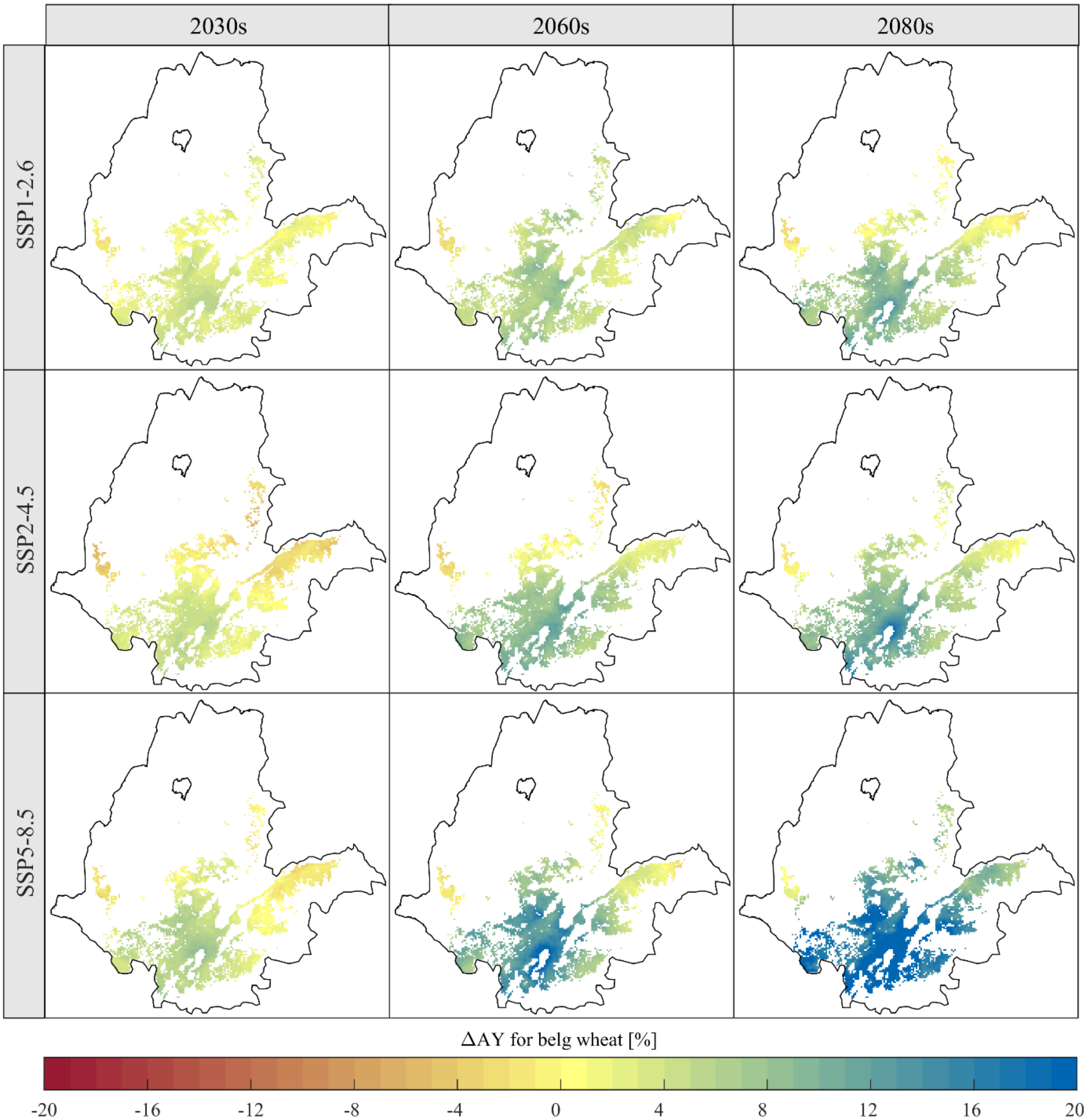

Figure S13: The same as Figure S10, but for wheat

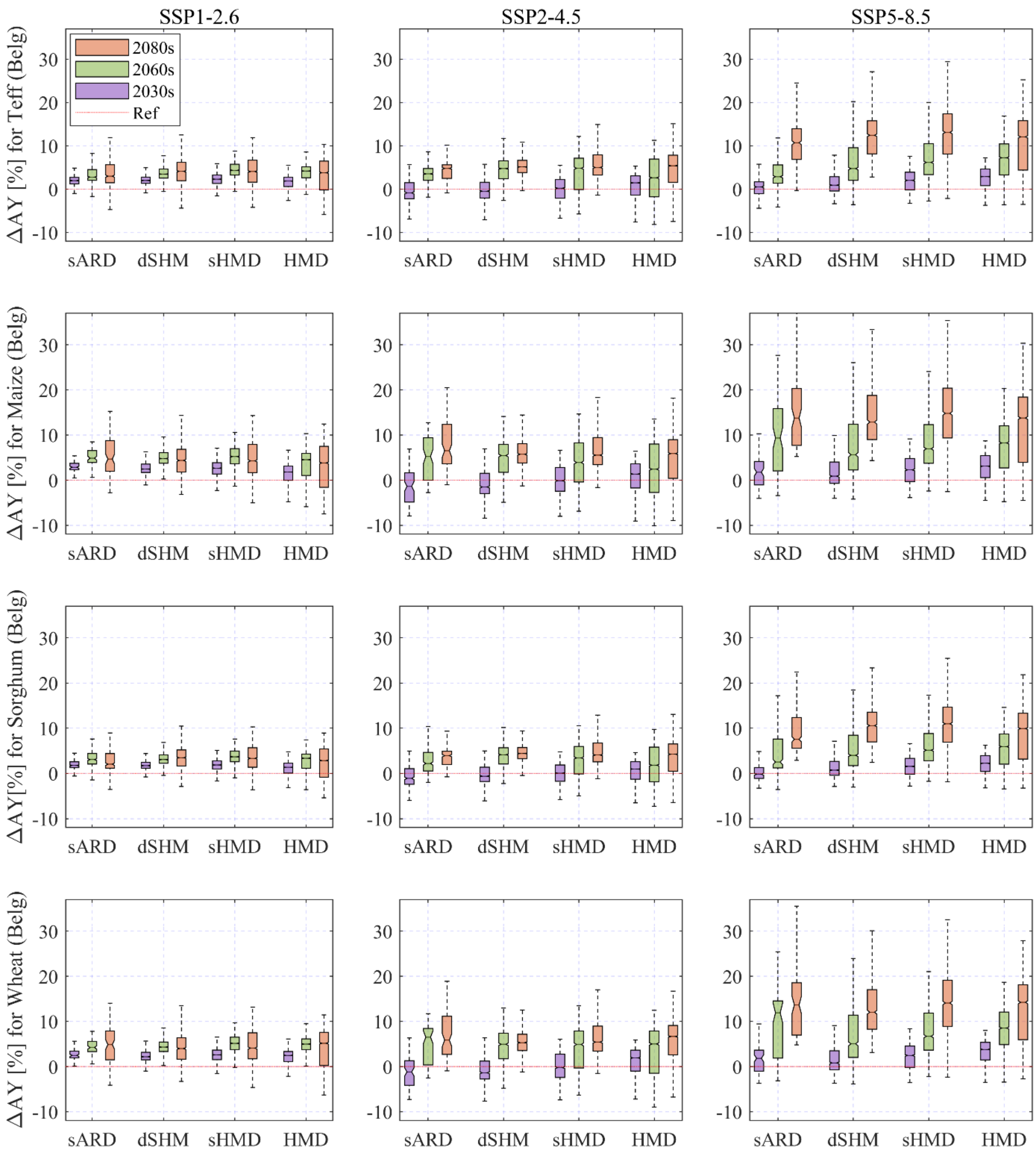

Figure S14: Boxplots of the projected changes in water-limited yields (AY) of the four major cereal crops produced in Ethiopia in different climatic regimes under the three SSPs during the three future periods, during the Belg growing season. Each boxplot represents the distribution of AY changes within Belg-producing areas for all grid cells in the respective climatic regime. Outlier values have been excluded.

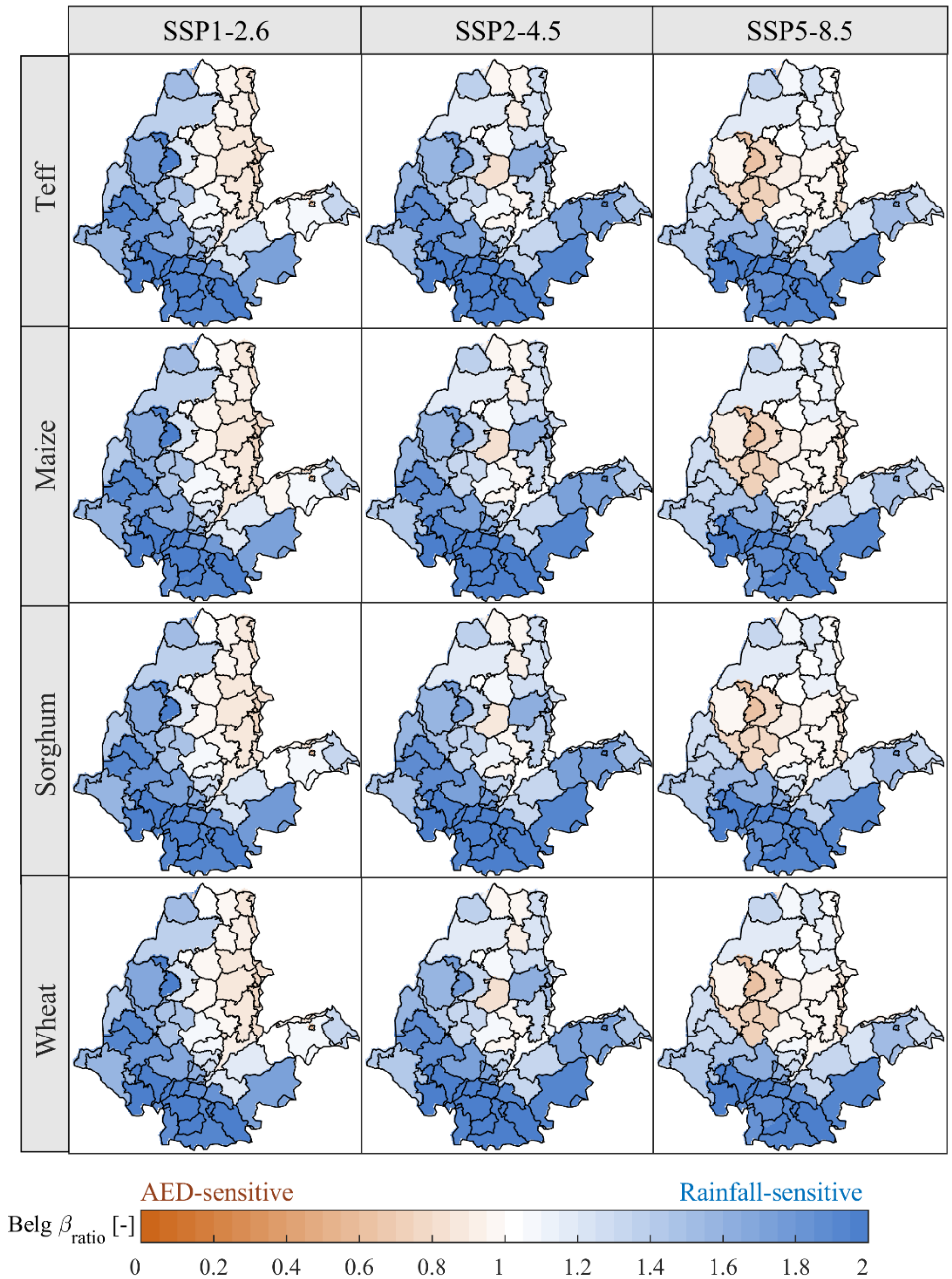

Figure S15: Area-averaged relative sensitivity (β_{ratio}) of water-limited attainable yields (AY) to rainfall and atmospheric evaporative demand (AED) for the Belg growing season at the administrative zone level under the low, intermediate, and high emission scenarios for teff, maize, sorghum, and wheat. The mapped values represent the average of β_{ratio} of all grid cells within each zone, and all three future periods. The short names of the 62 administrative zones within the RFA region of Ethiopia are indicated in Figure 1. The long names are listed in Table S1 of the supplementary material.

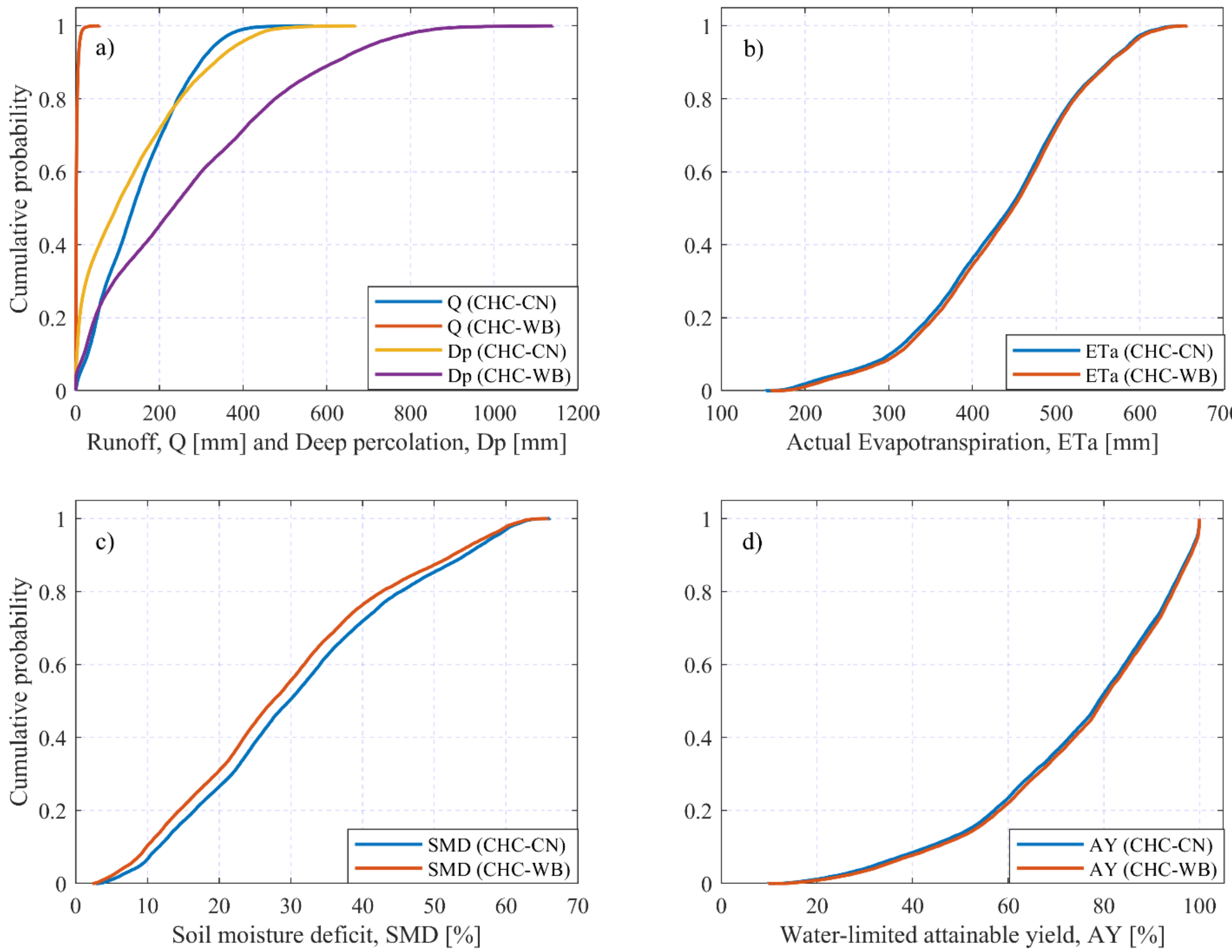

Figure S16: CDF plots of CN-based (CHC-CN) and water balance-based (CHC-WB) agrohydrological simulations for the Meher growing season, showing: a) surface runoff (Q) and deep percolation (Dp), b) actual evapotranspiration (ETa), c) soil moisture deficit (SMD), and d) water-limited attainable yield (AY). The values presented are the climatological means for the reference period (1981–2010) at each grid point across the rainfed agricultural regions of Ethiopia.

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