Climate change impacts on rainwater productivity (RP) across agricultural landscapes of Ethiopia

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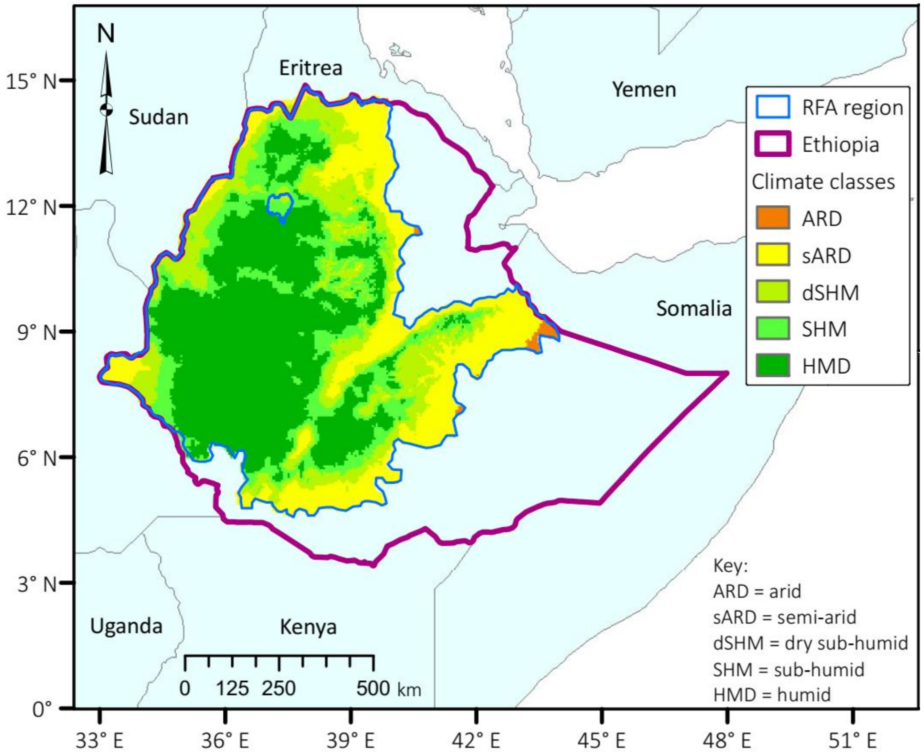
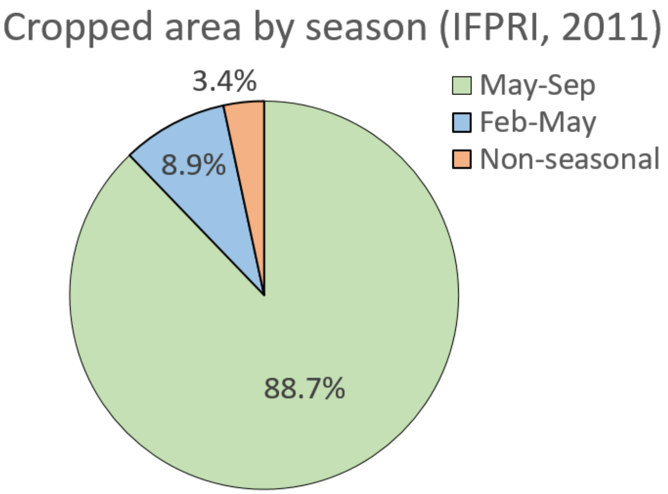
Context: Agriculture in Ethiopia

- ~80% of the population reliant on agriculture
- ~95% rainfed agriculture (RFA)



Cropping system

- Main season: May - Sep ('Meher')
- Short season: Feb - May ('Belg')



Top 4 major cereal crops

- Tef, maize, sorghum, wheat

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Research Questions

1. How will the climate variables over the agricultural regions of Ethiopia change in the future?

2. What is the impact on the rainwater productivity (RP) for cereal crops?

3. Which climate variable (precipitation or temperature) dominantly drives the changes in RP?

Data and Methods

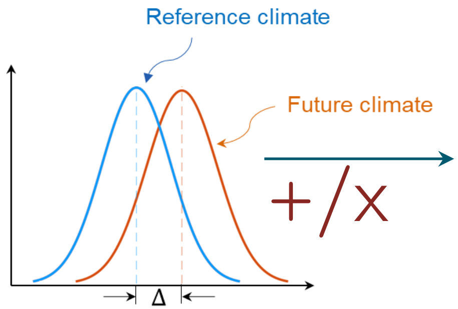
1. Climate downscaling (delta method)

25 CMIP6 models (Δ)

Scenario	Period
Historical	1981-2010
SSP1-2.6	2020-2049
SSP2-4.5	2045-2074
SSP5-8.5	2070-2099

	Model	Prec	Tmax	Tmin	Rs
1	ACCESS-CM2 (Australia)	x	x	x	x
2	AWI-CM-1-1-MR (Germany)	x	x	x	x
3	BCC-CSM2-MR (China)	x			x
4	CAMS-CSM1-0 (China)	x			x
5	CanESM5-CanOE (Canada)	x	x	x	x
6	CESM2 (USA)	x			x
7	CIESM		x	x	
8	CMCC-CM2-SR5 (Italy)	x			x
9	CMCC-ESM2 (Italy)	x	x	x	x
10	CNRM-CM6-1 (France)	x	x	x	x
11	CNRM-CM6-1-HR (France)	x	x	x	x
12	CNRM-ESM2-1 (France)	x	x	x	x
13	EC-Earth3-Veg-LR		x	x	
14	FGOALS-g3 (China)	x	x	x	x
15	FIO-ESM-2-0 (China)	x	x	x	x
16	GFDL-ESM4 (USA)	x	x	x	x
17	HadGEM3-GC31-LL (UK)	x	x	x	x
18	IITM-ESM (India)	x	x	x	x
19	INM-CM4-8		x	x	
20	INM-CM5-0 (Russia)	x	x	x	x
21	IPSL-CM6A-LR (France)	x	x	x	x
22	MIROC6 (Japan)	x	x	x	x
23	MIROC-ES2L (Japan)	x	x	x	x
24	MPI-ESM1-2-LR (Germany)	x	x	x	x
25	NESM3 (China)	x			x
26	NorESM2-MM (Norway)	x			x
27	TaiESM1	x			x
28	UKESM1-0-LL	x	x	x	x

Factors of change (Δ)



Reference climate (5km, daily)

- CHIRPS rainfall (Funk et al., 2015)
- BCE5 temperature* (Wakjira et al., 2023)
- ERA5 Land radiation and other variables (Muñoz-Sabater et al., 2021)

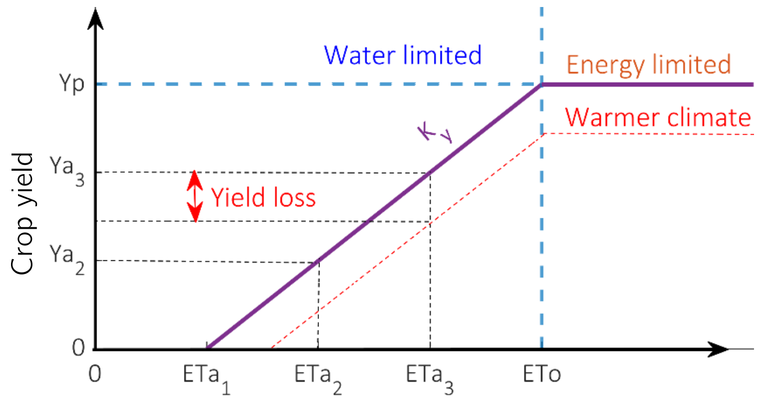
Downscaled future climate variables (5km, daily)

- Precipitation
- Maximum and minimum temperature
- Shortwave radiation

*BCE5 temperature is a daily maximum and minimum temperature dataset derived by bias adjusting and downscaling ERA5-Land temperature over Ethiopian domain for the period 1981-2010. Further details can be found at https://doi.org/10.1016/j.dib.2022.108844

2. Determination of rainwater productivity (RP)

Under moisture-limited conditions, yield is related to ET in a nearly direct manner (Hatfield and Dold, 2019)



Evapotranspiration = evaporative loss + Transpiration

Relative yield (Ya/Yp) was used a proxy for RP

Based on water productivity function (Steduto et al., 2009)

$$RP \sim \frac{Y_a}{Y_p} = 1 + K_y \left(\frac{ETa}{ETo} - 1 \right)$$

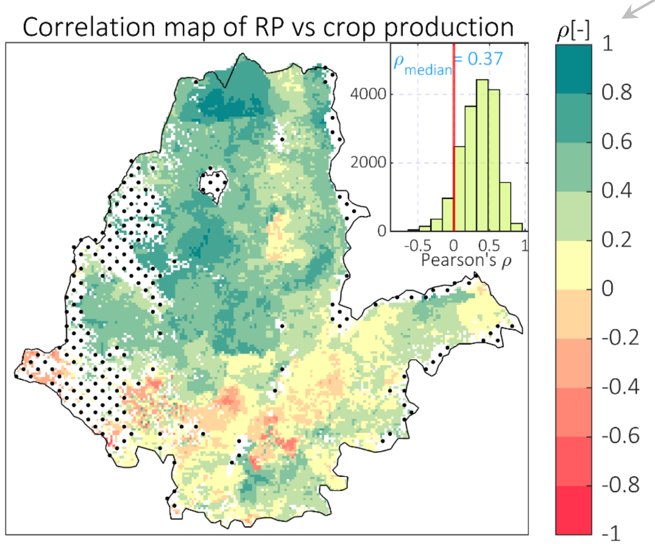
Reference ET (ETo)
Penman-Monteith (Allen et al., 1998)

Actual ET (ETa)
Curve number-based soil water balance model
$\Delta S = P - RO - ETa - Dp$

Climatic inputs

Soil and land use inputs

Correlation map of RP vs crop production



Based on gridded crop data of 1995-2010 (see Wakjira et al., 2021)

Ya = actual yield
Yp = potential yield
Ky = yield response factor (-)
P = precipitation (mm/day)
RO = runoff (mm/day)
Dp = deep percolation (mm/day)
ΔS = change in soil moisture (mm/day)

RP was determined at grid scale for the two growing seasons: Meher (May-Sep) and Belg (Feb-May) under the present and future climates

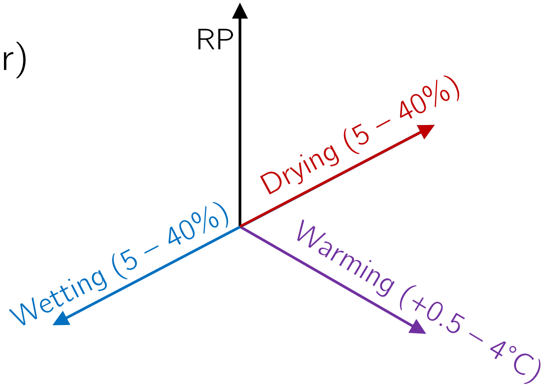
3. Climate sensitivity of RP

The One-At-a-Time (OAT) was used to assess which climate variable (rainfall or temperature) largely controls the changes in RP

Two change scenarios with 8 change levels were tested:

- Warm and dry climate (0.5-4°C warmer and 5-40% drier)
- Warm and wet climate (0.5-4°C warmer and 5-40% wetter)

The scenarios were built by perturbing the reference climate



RP was determined for each scenario and change level and sensitivity (Se) associated with each perturbation

$$\text{Se} = \frac{\%\text{change in output}}{\%\text{change in input}}$$

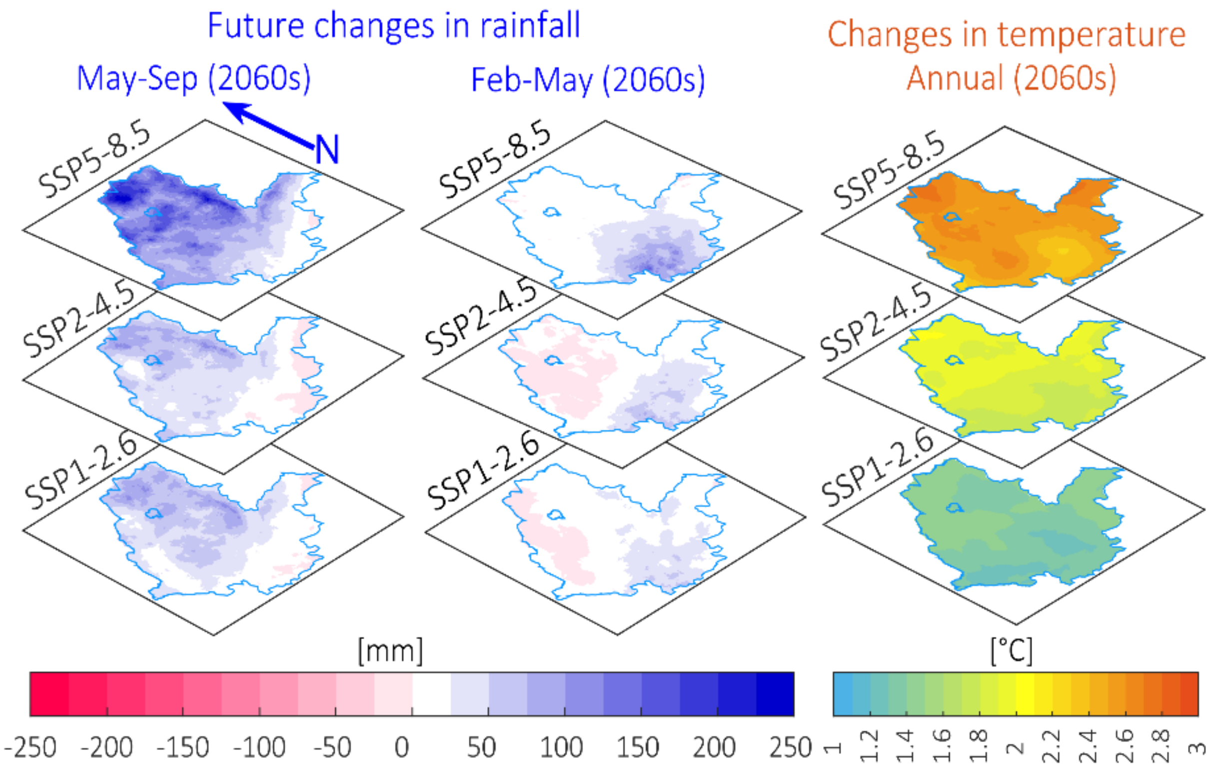
Sensitivity ratio (Sr) was computed for determine the relative sensitivity of RP to temperature and rainfall

$$\text{Sr} = \frac{\text{Se}_{rain}}{\text{Se}_{temp}}$$

Results and Discussions

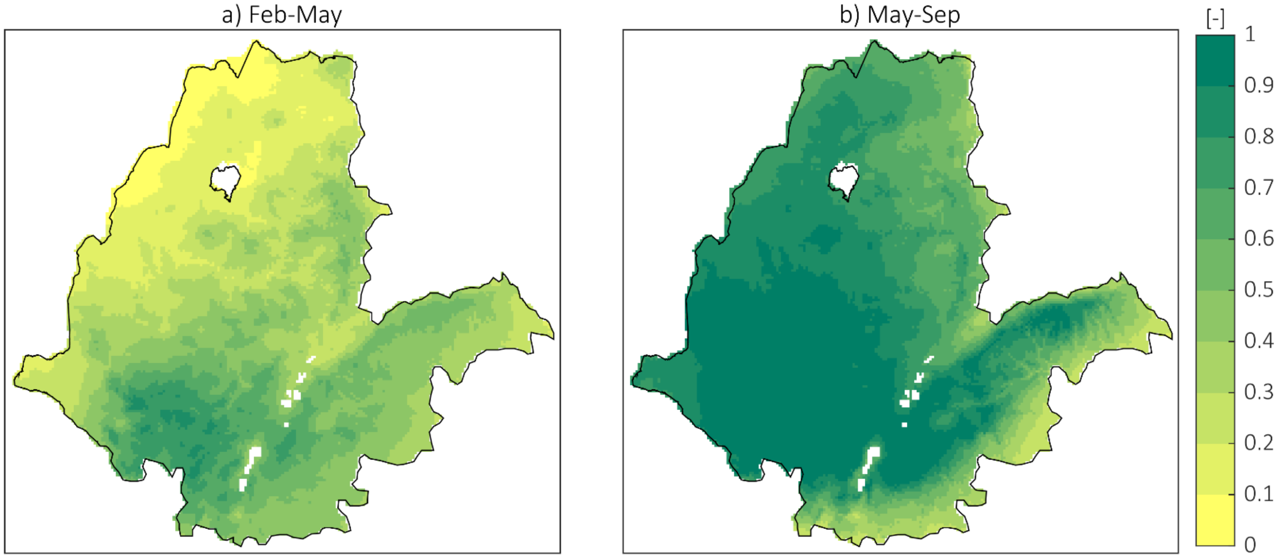
The future climate is likely to become warmer and wetter over the respective growing season in a given region

Note:
2030s = 2020-2049
2060s = 2045-2074
2080s = 2070-2099



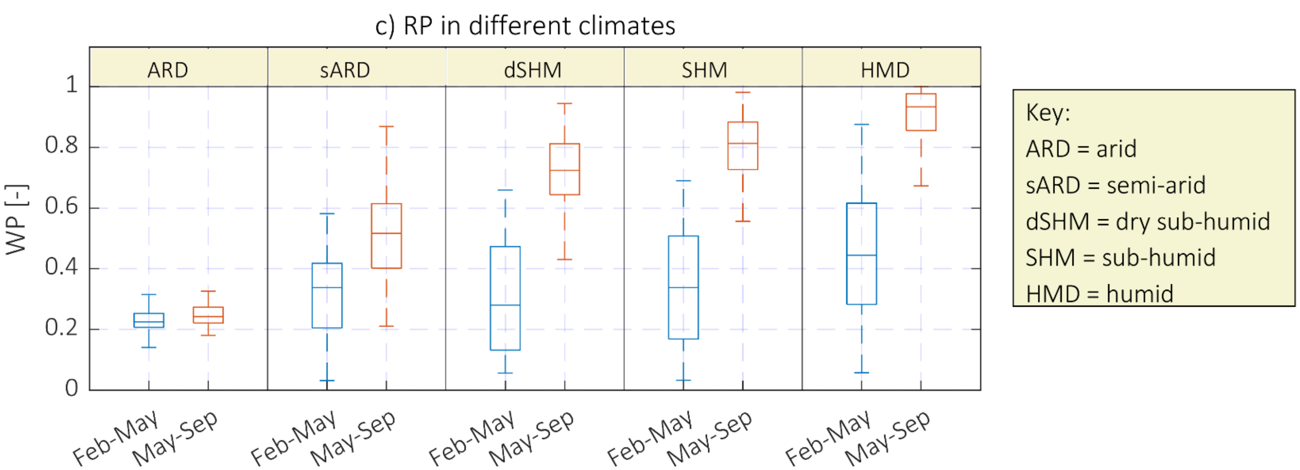
But dry regions are likely to remain warm and dry or become even drier

Rainwater productivity: climatology (1981-2010) for Ky = 1)



Crop	Ky
Tef	1.04
Maize	1.25
Sorghum	0.9
Wheat	1.15
Average	**1.09**

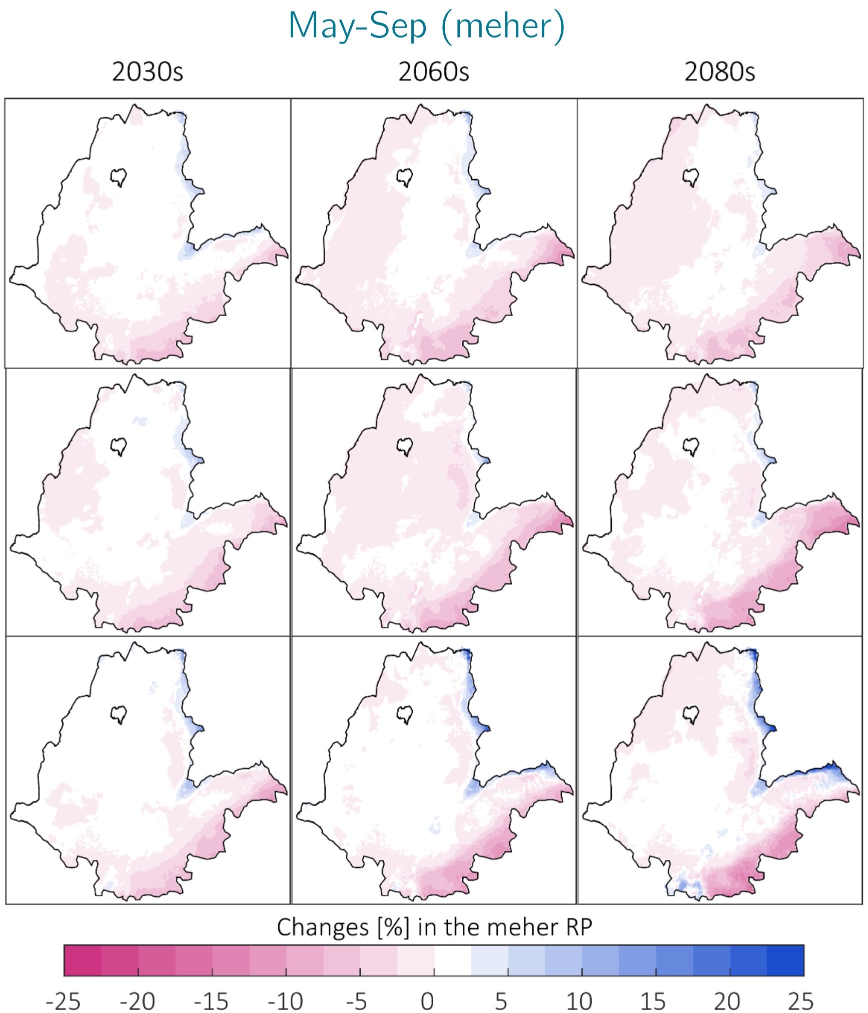
Allen et al.,(1998);
Araya et al., (2011)

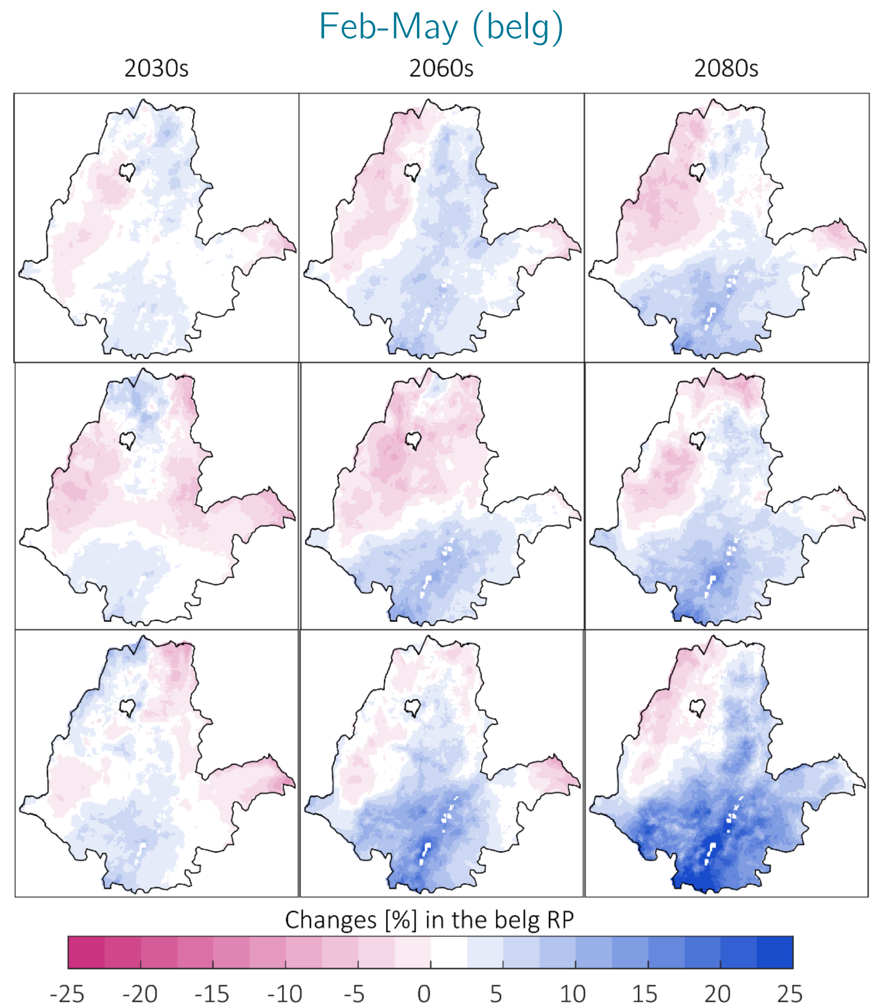


Note that when Ky = 1, RP equals evaporative stress index (the ratio of ETa and ETo).

The May-Sep WP is more than twice of the one in the Feb-May growing season

How will RP for an average cereal crop (Ky=1) change in the coming decades?





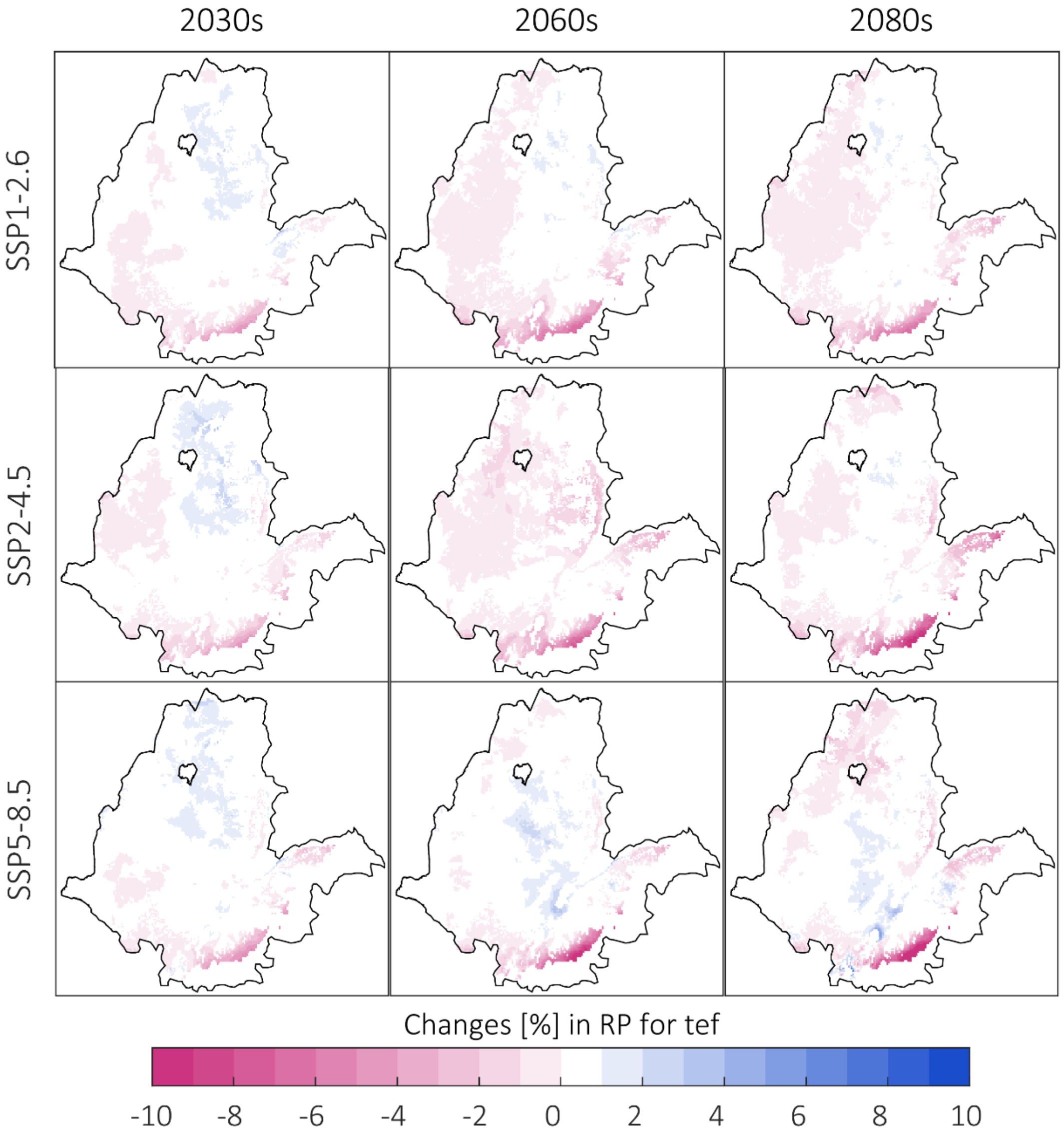
May-Sep: largely a decrease or minor change over the entire region
Feb-May: increase over the belg regions towards the end of the century and all scenarios

How will the individual crop RP change under the future climate?

Meher tef

Minor increase or no change over the tef hotspot regions in 2030s under all scenarios

Decreasing tendency by the mid and end of the century over the western part of the tef regions

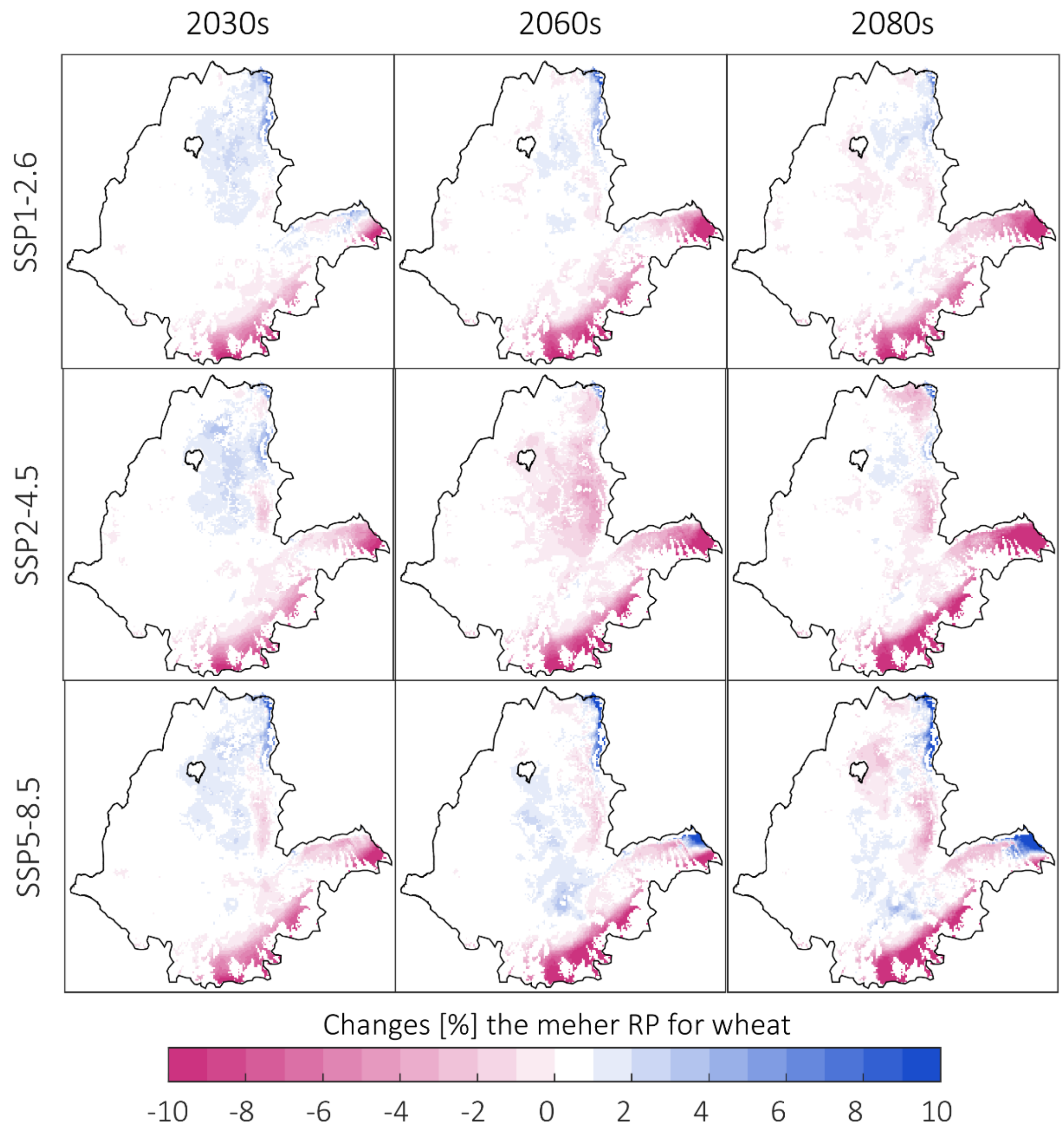


How will the individual crop RP change under the future climate?

Meher wheat

Up to 3% increase over the meher regions in 2030s under all scenarios

Considerable decrease (up to 10%) in the semi-arid climate in the future periods



Which climate variable is the dominant driver of the changes in RP?

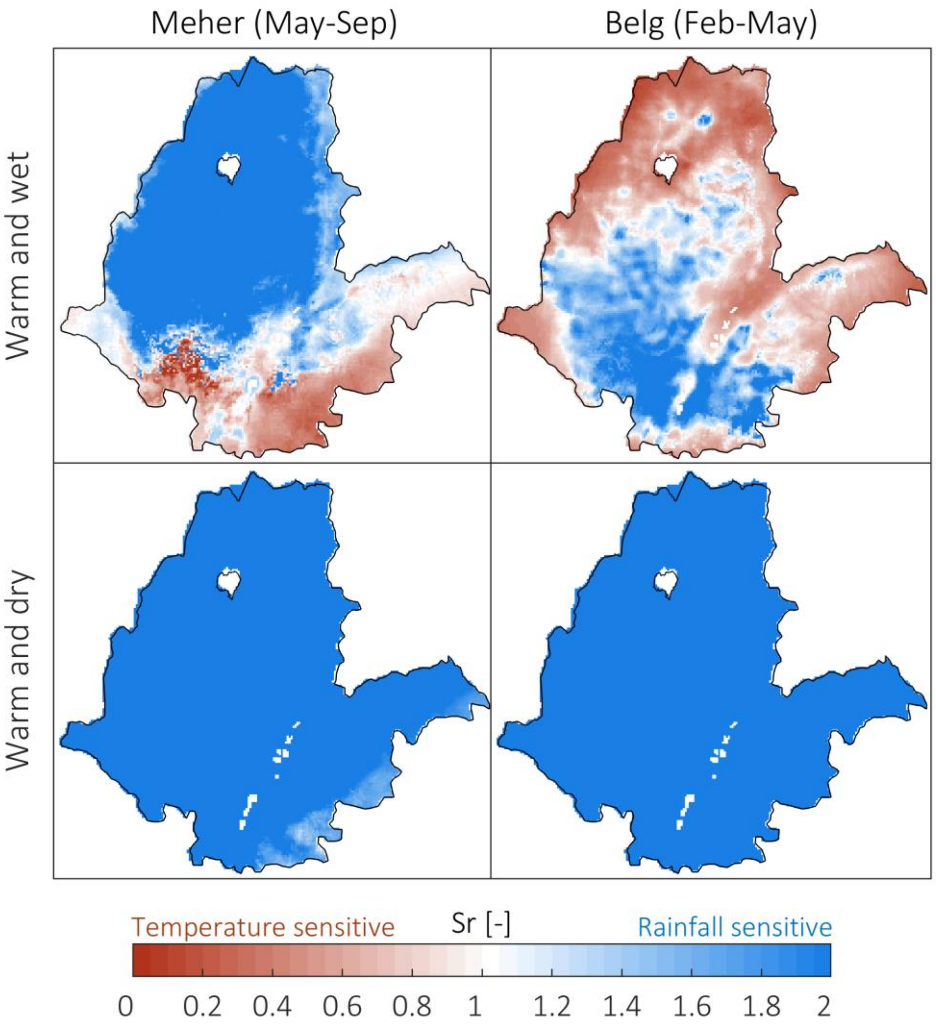
Under warming and wetting climate

- In regions with seasonal (unimodal) rainfall, the meher RP is sensitive to precipitation
- In regions with erratic rainfall and semi-arid climate, temperature controls the meher RP
- In belg, RP is controlled by temperature in dry regions and by precipitation in wet regions

Under warming and drying climate

- Changes in precipitation drives changes in RP in both in meher and belg season, regardless of the rainfall pattern and climate

Sensitivity ratio (Sr) across the agricultural landscape



Conclusions

The future climate

- Warmer and wetter during the two growing seasons
- Dry regions remain dry in both meher and belg seasons

Future water productivity

- Decrease or no change during the main growing season (May-Sep)
- Increase (by 5-25%) in the shorter growing season

Sensitivity to precipitation and temperature

- Precipitation dominantly drives the changes in warming and drying climate
- Sensitivity depends on the rainfall regime in warming and wetting climate

For questions please reach out to
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References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration, Irrigation and Drainage Paper No. 56. Rome.

Araya, A., Stroosnijder, L., Girmay, G., Keesstra, S.D., 2011. Crop coefficient, yield response to water stress and water productivity of teff (Eragrostis tef (Zucc.). Agric. Water Manag. 98, 775–783. https://doi.org/10.1016/j.agwat.2010.12.001

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., Michaelsen, J., 2015. The climate hazards infrared precipitation with stations - A new environmental record for monitoring extremes. Nat. Sci. Data 2. https://doi.org/10.1038/sdata.2015.66

Hatfield, J.L., Dold, C., 2019. Water-use efficiency: Advances and challenges in a changing climate. Front. Plant Sci. 10, 1–14. https://doi.org/10.3389/fpls.2019.00103

Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D.G., Piles, M., Rodríguez-Fernández, N.J., Zsoter, E., Buontempo, C., Thépaut, J.N., 2021. ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. Earth Syst. Sci. Data 13, 4349–4383. https://doi.org/10.5194/essd-13-4349-2021

Steduto, P., Hsiao, T.C., Raes, D., Fereres, E., 2009. Aquacrop-the FAO crop model to simulate yield response to water: I. concepts and underlying principles. Agron. J. 101, 426–437. https://doi.org/10.2134/agronj2008.0139s

Wakjira, M.T., Peleg, N., Burlando, P., Molnar, P., 2023. Gridded daily 2-m air temperature dataset for Ethiopia derived by debiasing and downscaling ERA5-Land for the period 1981–2010. Data Br. 46, 108844. https://doi.org/10.1016/j.dib.2022.108844