

CAN IRRIGATION MODERNIZATION OFFSET CLIMATE-DRIVEN INCREASES IN CROP WATER DEMAND? EVIDENCE FROM TÜRKİYE

LA MODERNISATION DE L'IRRIGATION PEUT-ELLE COMPENSER L'AUGMENTATION DES BESOINS EN EAU DES CULTURES DUE AU CLIMAT? ÉLÉMENTS PROBANTS POUR LA TÜRKİYE

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ABSTRACT

Türkiye's irrigated agriculture is under pressure from climate-driven increases in evapotranspiration and decreases in effective precipitation, as well as existing groundwater stress, especially in key crop production regions like Konya. This study examines whether irrigation modernization can compensate for the expected increases in net irrigation requirement (NIR) for two important crops: sugar beet and maize. NEX-GDDP-CMIP6 climate data from the MPI-ESM1-2-LR model is used for a historical baseline period from 1990 to 2014 and four future scenarios: SSP245 and SSP585 for the periods 2030 to 2060 and 2070 to 2100. Crop evapotranspiration is estimated using the Hargreaves-Samani method, and effective precipitation is estimated using the FAO/AGLW method. NIR is calculated at a resolution of 0.25° across Türkiye. The results were combined for the top-producing provinces and summarized using production-weighted averages. Under SSP245 and near-term SSP585 conditions, projected NIR increases are moderate and can be offset by 20% water savings, but 30% water savings are needed to safely mitigate the worst-case SSP585, 2070-2100 scenario. Results at the provincial level flag Konya as a critical exposure point due to its significant share of production in both crops. The findings indicate that irrigation modernization is a necessary measure, but improvements in field-scale efficiency should not be regarded as guaranteed water savings at the basin scale without ensuring efficient water allocation controls and crop planning.

Keywords: Climate change; Irrigation requirement; NEX-GDDP-CMIP6; Sugar beet; Maize; Türkiye; Modernization; Hargreaves–Samani,

RÉSUMÉ

L'agriculture irriguée en Türkiye subit la pression de l'augmentation de l'évapotranspiration et de la diminution des précipitations efficaces dues au climat, auxquelles s'ajoutent les contraintes existantes sur les eaux souterraines, en particulier dans les principales régions de production agricole telles que Konya. Cette étude examine si la modernisation de l'irrigation peut compenser les augmentations attendues des besoins nets d'irrigation (NIR) de deux cultures importantes : la betterave sucrière et le maïs. Les données climatiques NEX-GDDP-CMIP6 issues du modèle MPI-ESM1-2-LR sont utilisées pour une période historique de référence allant de 1990 à 2014 et pour quatre scénarios futurs : SSP245 et SSP585 sur les périodes 2030-2060 et 2070-2100. L'évapotranspiration des cultures est estimée à l'aide de la méthode de Hargreaves-Samani, et les précipitations efficaces au moyen de la méthode FAO/AGLW. Les NIR sont calculés à une résolution de 0,25° sur l'ensemble du territoire de Türkiye. Les résultats ont été combinés pour les provinces les plus productrices et synthétisés sous forme de moyennes pondérées par la production. Dans le scénario SSP245 et à court terme dans le scénario SSP585, les augmentations projetées des NIR sont modérées et peuvent être compensées par des économies d'eau de 20 %, mais des économies de 30 % sont nécessaires pour atténuer de manière fiable le scénario le plus défavorable, SSP585 sur la période 2070-2100. Les résultats à l'échelle provinciale désignent Konya comme un point d'exposition critique en raison de sa part

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importante dans la production des deux cultures. Les conclusions indiquent que la modernisation de l'irrigation est une mesure nécessaire, mais que les améliorations de l'efficacité à l'échelle de la parcelle ne doivent pas être considérées comme des économies d'eau garanties à l'échelle du bassin sans dispositifs efficaces de contrôle de l'allocation de l'eau et de planification des cultures.

Mots clés : Changement climatique; Besoins d'irrigation; NEX-GDDP-CMIP6; Betterave sucrière; Maïs; Türkiye; Modernisation; Hargreaves–Samani.

1. INTRODUCTION

Irrigation accounts for 75% of annual water use in Türkiye (Acar et al., 2010; Dedemen & Kocak, 2026). Hence, agriculture is the most vulnerable sector to changes in water availability induced by climate change. Pilevneli et al. (2023) predicted that the country might face a shift from a 14.6 km³ irrigation-water surplus per year to a 57.3 km³ deficit under the RCP 8.5 scenario by 2071–2100, which could lead to detrimental effects on agricultural production and income.

Sugar beet, which is one of Türkiye's strategic crops, cannot be cultivated without irrigation. Similarly, maize is among the two crops most vulnerable to climate-driven water deficit (Pilevneli et al., 2023). The spatial distribution of corn and sugar beet production appears to be uneven across the country. In fact, Konya province alone accounts for 34.9% of national sugar beet and 23.1% of national maize production (TURKSTAT, 2025). Thus, any severe climate impacts in Konya could jeopardize the national food security of these critical crops. However, the region is already operating beyond its sustainable hydrological limits even without the effects of future climate change. In the Konya Closed Basin, agriculture accounts for more than 90% of water use, and groundwater resources are indispensable for meeting water demand (Yazici & Taner, 2023). It has been reported that groundwater levels have declined by 1–3 m per year in some sub-basins (Çelebi, 2016), driving regional land subsidence of up to 90 mm per year and the formation of more than 660 sinkholes (Orhan et al., 2023). The pressure on groundwater resources is mainly attributed to surging irrigation-dependent sugar beet and maize production (Acar et al., 2010). At the Mediterranean scale, Fader et al. (2016) showed that climate change alone would raise irrigation requirements by 4–18%, and countries including Türkiye have up to 35% water-saving potential by improving irrigation efficiency through modernization. Çetin et al. (2024) provided direct empirical evidence from Türkiye by comparing a surface-irrigated scheme with a modernized one, emphasizing that modernization can reduce water use per hectare by 47%. These findings indicate that modernization is not just a technical upgrade but also an imperative for controlling the agricultural sector's water demand and making it more resilient to water-related pressures induced by climate change.

Although the benefits of irrigation modernization are well established in previous studies, the extent to which irrigation modernization can compensate for the increasing water demands of Türkiye's strategic crops under climate change remains unquantified. Quantifying this potential is essential to accurately prioritize future modernization investments and to identify highly vulnerable regions where modernization alone is not sufficient to meet increasing crop water demand, necessitating a change in the existing crop pattern.

Specifically, three gaps identified in previous studies are addressed in the present work. First, the Penman–Monteith (PM) equation, which is widely used to estimate reference evapotranspiration, requires many meteorological variables (temperature, radiation, humidity, and wind speed). However, these data are often unavailable, incomplete, or of low quality, which prevents the equation's use across regions with limited data availability (Córdova et al., 2015; Paredes et al., 2018; Ferreira et al., 2018). In fact, most Turkish climate-irrigation studies using the PM equation had to rely on single-station weather data for which full PM inputs are available (e.g., Arslan, 2020; Gorguner et al., 2020), limiting their usefulness for national-scale spatiotemporal analysis. When the required meteorological inputs for the PM method are unavailable or unreliable, the Hargreaves–Samani (H-S) method, which requires only temperature data, can be used instead. The H-S method can accurately approximate PM-based estimates in Mediterranean and semi-arid regions (Almorox & Grieser, 2016; Koç & Erkan Can, 2023; Paredes et al., 2018), enabling grid-based, national projections that single-station studies

lack. Second, the modernization-offset framing — explicitly comparing farm-scale efficiency-gain scenarios against grid-by-grid climate-driven increases in net irrigation requirement (NIR) — has been applied at the Mediterranean (Fader et al., 2016) and global scales (Jägermeyr et al., 2015), but not at the province scale for Türkiye's strategic irrigated crops. Third, as noted by the growing body of literature, the efficiency paradox associated with irrigation modernization deserves attention. This paradox manifests itself as increased water consumption at the basin scale despite the improvements in on-farm irrigation efficiency (Hoffmann & Villamayor-Tomas, 2023; Sanchis-Ibor et al., 2024; Berbel et al., 2018; Santini et al., 2025). This issue is usually overlooked by Turkish climate-irrigation studies.

To address the abovementioned gaps, the present paper: (i) computes grid-by-grid, national-scale NIR projections for sugar beet and maize across Türkiye by applying the temperature-based Hargreaves-Samani method to downscaled NEX-GDDP-CMIP6 climate data. (ii) quantifies the potential of modernization investments in mitigating climate-driven NIR increases at the province level using different rates of post-modernization water saving scenarios, and (iii) interprets the findings within the efficiency-paradox framework to clarify what the results do and do not imply for future water policy.

2. MATERIALS AND METHODS

2.1. Climate data

In this study, the NASA NEX-GDDP-CMIP6 dataset, designed for regional impact and adaptation analyses, is used, as it provides bias-corrected CMIP6 projections at 0.25° resolution (Thrasher et al., 2022). Within this ensemble, the MPI-ESM1-2-LR general circulation model (GCM) was selected as an advanced Earth system model with updated atmosphere–land–hydrology schemes and realistic equilibrium climate sensitivity (Mauritsen et al., 2019), and because it is among the GCMs that reproduce precipitation characteristics comparatively well over the study region (Tian et al., 2023). Four variables were extracted: monthly mean air temperature, monthly mean of daily maximum and minimum temperatures, and monthly total precipitation. Five periods were defined: a historical baseline (1990–2014), and four future periods — SSP245 near-term (2030–2060), SSP245 far-term (2070–2100), SSP585 near-term (2030–2060), and SSP585 far-term (2070–2100). The spatial domain encompassed the Türkiye bounding box (lat: 36°–42°; lon: 26°–45°), yielding a 24 × 76 grid of 0.25° cells.

2.2. Reference evapotranspiration (ET_0)

Hargreaves & Samani (1985) equation is used to calculate monthly reference evapotranspiration (ET_0):

$$ET_0 = 0.023 R_a (T_{\text{mean}} + 17.8) (T_{\text{max}} - T_{\text{min}})^{0.5}$$

R_a is the extraterrestrial radiation (mm/day equivalent) computed using mid-month Julian day and grid-cell latitude based on FAO-56 Annex 2 (Allen et al., 1998). The Hargreaves-Samani method (H-S) is recommended when the available data are limited or unreliable, and therefore, the standard Penman-Monteith equation cannot be used (Aydın, 2021). However, some studies, such as Paredes et al. (2018) and Awal et al. (2020) recommend that H-S method should be calibrated against the Penman-Monteith method, since it introduces systematic biases in the uncalibrated form. We address this limitation by reporting relative changes (Δ %) rather than absolute values for the main findings.

2.3. Crop coefficients (K_c), crop calendar, and crop ET (ET_c)

Daily crop coefficient (K_c) values are calculated using the FAO-56 segmented-curve method (Allen et al., 1998). K_c values were then aggregated to monthly averages to match the NEX-GDDP monthly time step. The resulting K_c curves are shown in Figure 1. For sugar beet, stage K_c and stage-length parameters were taken directly from FAO-56 (Allen et al., 1998; Tables 11–12, Mediterranean climate). The planting date of 1 April corresponds to standard Konya basin practice (Yamaç, 2020).

For maize, stage Kc and stage-length parameters were taken from Koç et al. (2022), who measured weighing-lysimeter ET_c and Kc for first-crop maize at Çukurova University Adana research station (Mediterranean Türkiye). Planting date was set to 15 April, consistent with the typical first-crop maize practice in southern and inner-Anatolian Türkiye.

2.4. Effective precipitation

Effective precipitation (P_{eff}) is computed using the FAO/AGLW method (Muratoglu et al., 2023):

$$P_{eff} = 0.6 P - 10 \quad (P \leq 70 \frac{\text{mm}}{\text{month}})$$

$$P_{eff} = 0.8 P - 24 \quad (P > 70 \frac{\text{mm}}{\text{month}})$$

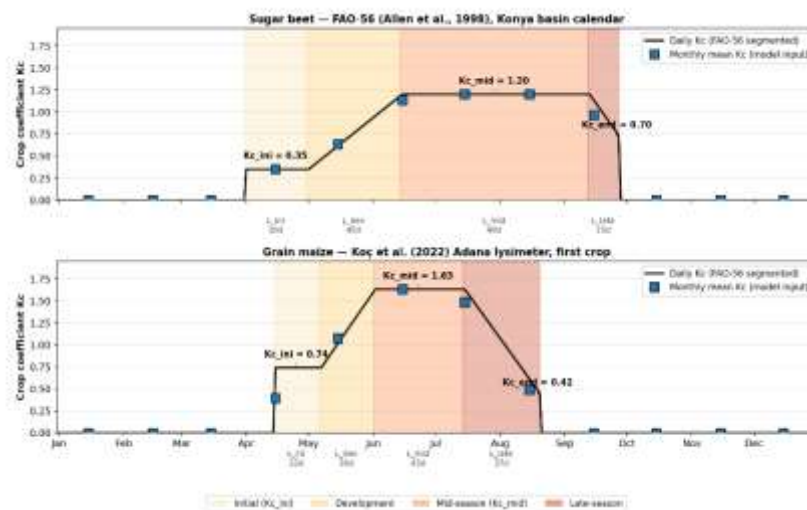


Figure 1. FAO-56 segmented Kc curves used in the analysis

2.5. Net irrigation requirement (NIR) and change calculation

Net irrigation requirement was computed monthly as:

$$NIR = \max(ET_c - P_{eff}, 0)$$

These monthly values were summed to calculate annual totals, which were then averaged across the respective years of each scenario (e.g., SSP245 2030–2060) to obtain the mean annual NIR per grid cell for each study period. NIR represents the field-scale net water depth required at the root zone. The corresponding gross irrigation withdrawal (which accounts for system inefficiencies) is evaluated in the modernization analysis below. Climate-driven changes (Δ) were computed against the historical baseline (1990–2014) as absolute differences for temperature and relative percentages for all other variables.

2.6. Modernization offset analysis

To quantify the potential of irrigation modernization to offset climate change, an offset ratio is defined for each cell, period, and crop in the analysis as shown below.

$$\text{saving} = NIR_{\text{historical}} \times \text{saving rate}$$

$$\Delta_{\text{future}} = NIR_{\text{future}} - NIR_{\text{historical}}$$

$$\text{offset ratio} = \frac{\text{saving}}{\Delta_{\text{future}}}$$

Sensitivity of the offset ratio to different modernization saving rates is evaluated by including varying modernization saving rates in the analysis (10%, 20%, 30%, and 40%). These values are reported by Çetin et al. (2024) and reflect the range of the actual savings rates observed in post-modernization scenarios. Offset ratios greater than 1 indicate that water savings from modernization fully compensate for the NIR increase stemming from climate change. Offset ratios less than 1 indicate only partial offset potential.

2.7. Province-level aggregation

The top seven producer provinces for sugar beet and maize are analyzed. Grid cells that lie within the boundary of each designated province are identified, and the corresponding spatial average of change in NIR (delta NIR) is reported for each of the top producer provinces. Finally, to generalize the findings to the country scale, a production-weighted average is computed by weighting the province-level results according to their respective national production shares.

3. RESULTS

3.1. Baseline climate and irrigation water requirement

The baseline maps shown in Figure 2 enable interpretation of future water demand for irrigation. The historical baseline period (1990-2014) indicates well-known climatic heterogeneity across Türkiye. While temperature is higher in the southern and particularly southeastern regions of the country, precipitation is higher along the coasts, but inner, southern, and southeastern parts are characterized by lower precipitation and higher evaporative demand. Evapotranspiration is particularly high in the southern and southeastern parts of the country, indicating that these regions already operate under a more water-stressed climatic baseline.

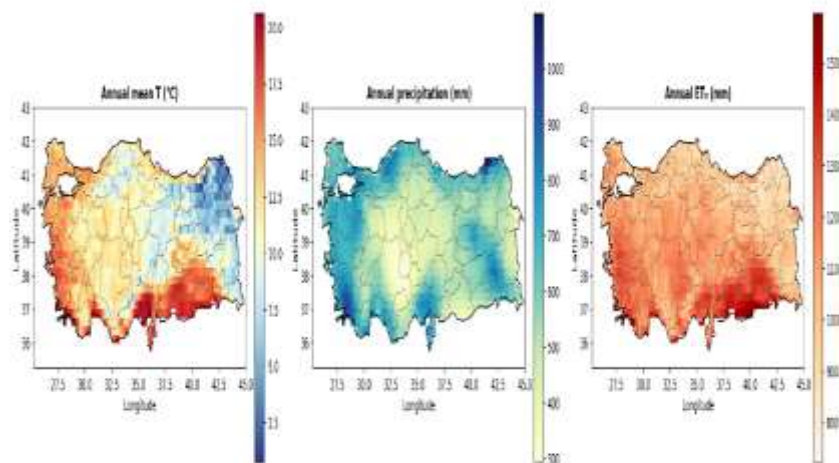


Figure 2. Baseline climatology of Türkiye, 1990-2014 (NEX-GDDP-CMIP6, MPI -ESM1-2-LR)

3.2. Country-scale projected climatology changes under climate change scenarios

Figure 3 shows projected changes in annual mean temperature, precipitation, and reference evapotranspiration under climate change scenarios for near (2030-2060) and far (2070-2100) future periods. Under SSP245, changes remain relatively moderate, especially in the near-term period. Under SSP585, and particularly by 2070–2100, warming becomes substantially stronger. Precipitation

declines strongly across much of central, southern, and southeastern Türkiye, and ET_0 increases substantially. The simultaneous occurrence of higher reference evapotranspiration and lower precipitation implies irrigation water requirement will increase in the future.

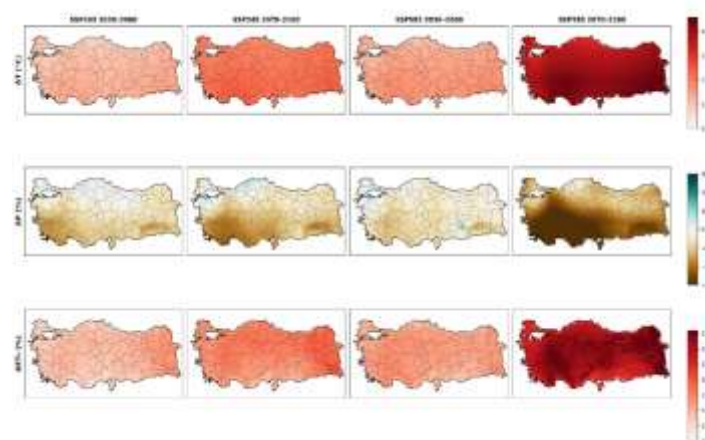


Figure 3. Projected changes in annual mean temperature, precipitation, and reference evapotranspiration under SSP245 and SSP585 relative to the historical 1990–2014 baseline

3.3. Spatial pattern of NIR change

Projected changes in net irrigation requirement are shown in Figure 4. The top seven producer provinces are highlighted in blue for sugar beet and green for maize. Results show that, in the near future (2030-2060), under SSP245 and SSP585, NIR increases moderately across the country. However, the increase becomes much more significant across central, northern, and eastern parts of the country under SSP585 far-future period (2070-2100). Several major sugar-beet and grain-maize production areas fall within zones of substantial future increases in irrigation requirement.

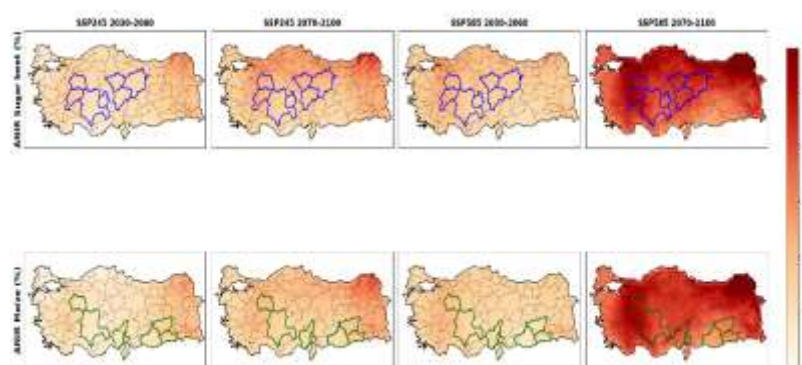


Figure 4. Projected change in net irrigation requirement by crop and period. Top row shows sugar beet and bottom row shows maize

3.4. Province-level results

Figure 5 and Table 1 show projected changes in NIR by top-producing provinces under SSP245 and SSP585 end-of-century (for 2070-2100 period). The SSP585 2070–2100 scenario results shown in Table 1 is selected for detailed province-level reporting because they represent the highest irrigation-demand stress case. For sugar beet, all seven top-producing provinces experience substantial NIR increases, ranging from +18.7 % in Aksaray to +24.9 % in Afyonkarahisar. Konya, which accounts for 34.9 % of national sugar-beet production among the selected producer provinces, shows a sugar-beet NIR increase from 806.5 mm/yr to 968.7 mm/yr, corresponding to +20.1 %. For maize, the range is more heterogeneous. Konya shows a +21.0 % increase, while Şanlıurfa, Mardin, and Diyarbakır show

lower relative increases of +13.3 %, +14.5 %, and +16.3 %, respectively. These lower percentage increases occur despite high absolute NIR levels because these provinces already have high baseline irrigation requirements (951-986 mm/yr). Eskişehir, an inner-Anatolian province, records the highest relative NIR increase in maize, +24.5%, although its baseline NIR (723 mm/yr) is lower than that of the semi-arid southeastern provinces.

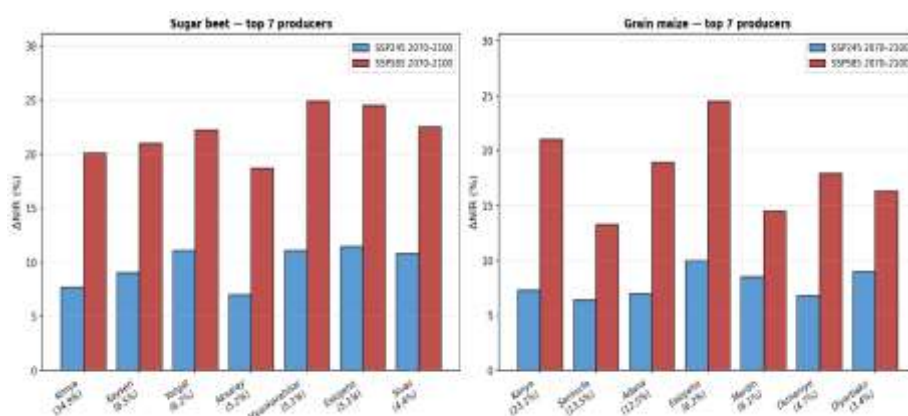


Figure 5. Projected changes in NIR by top-producing provinces under SSP245 and SSP585 end-of-century.

Table 1. Province-level NIR results under SSP585 2070–2100.

Crop Province	Production share (%)	Historical NIR (mm/yr)	Future NIR (mm/yr)	ΔNIR (%)
Sugar beet				
Konya	34.9	806.5	968.7	+20.1
Kayseri	6.5	800.5	968.3	+21
Yozgat	6.2	772.7	944.1	+22.2
Aksaray	5.2	837.8	994.4	+18.7
Afyonkarahisar	5.1	767.9	958.9	+24.9
Eskişehir	5.1	749.5	932.9	+24.5
Sivas	4.4	744.6	912.1	+22.5
Maize				
Konya	23.1	772.1	934.0	+21.0
Şanlıurfa	13.5	988.8	1,120.4	+13.3
Adana	12.5	773.0	918.9	+18.9
Eskişehir	6.2	723.1	899.9	+24.5
Mardin	6.1	951.1	1,088.8	+14.5
Osmaniye	4.7	814.3	959.7	+17.9
Diyarbakır	3.4	883.0	1,027.3	+16.3

3.5. Modernization offset analysis

Maps for the modernization offset ratio for sugar beet and maize under SSP585, for the period of 2070-2100 are given in Figure 6. The modernization offset ratio compares the potential saving from irrigation modernization with the projected climate-driven increase in NIR. An offset ratio of 1.0

indicates that modernization savings are equal to the projected increase; values below 1.0 indicate partial offset, while values above 1.0 indicate that savings exceed the climate-driven increase.

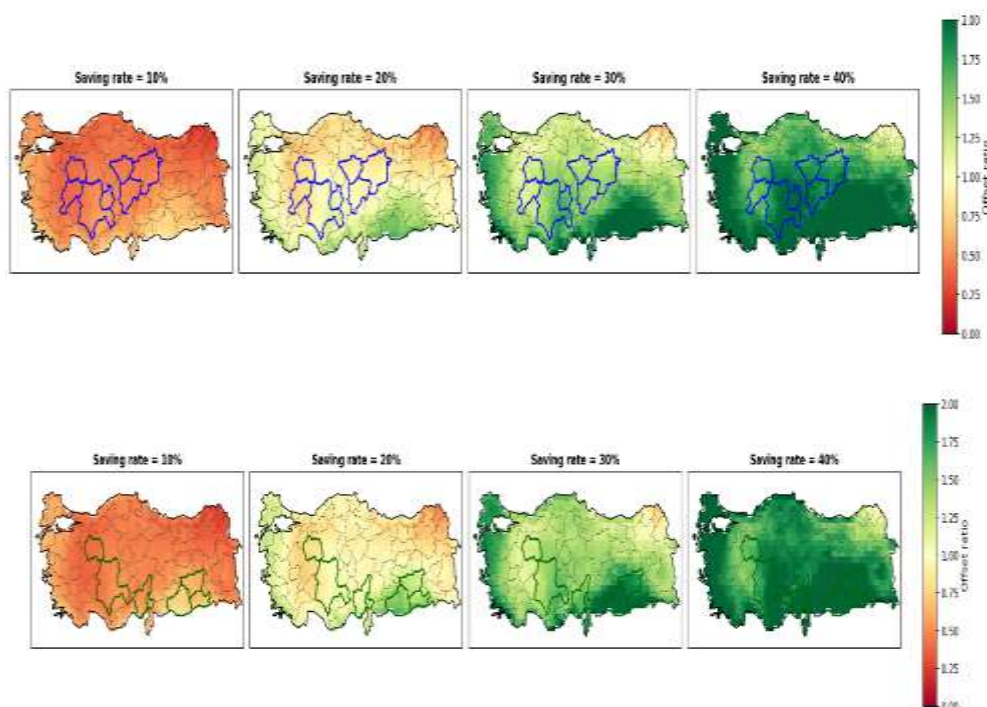


Figure 6. Modernization offset ratio for sugar beet (Top) and maize (Bottom) under SSP585, 2070–2100.

The offset maps show a clear transition between insufficient and sufficient modernization savings. At 10 % saving, most areas remain below full offset. At 20 % saving, many regions either meet or come close to the threshold for full offset, although some areas still fall short. At 30 % saving, a majority of the country transitions to full-offset conditions. At a 40% reduction, a sizable buffer is created to counter the anticipated climate-related increases. This trend is consistent for both sugar beet and maize, as the offset ratio mainly hinges on the comparison between baseline NIR and projected future NIR increases.

3.6. Production-weighted signal across top-producing provinces

The top-producer production-weighted results provide a more crop-policy-oriented picture than the country land-mean results. Figure 7 and Table 2 show the scenario-dependent escalation of irrigation demand. Under SSP245, the projected NIR increases remain relatively modest. For sugar beet, production-weighted NIR increases are +5.59 % in 2030–2060 and +8.83 % in 2070–2100. For maize, the corresponding increases are +4.79 % and +7.47 %. Under SSP585 near-term, the production-weighted increase is +8.67 % for sugar beet and +6.46 % for maize. Under SSP585 end-of-century, however, the production-weighted increase rises sharply to +21.12 % for sugar beet and +18.43 % for maize.

A key observation is that **ΔNIR exceeds ΔETc in every period**. For sugar beet under SSP585 end-of-century, ΔETc is +16.94 % while ΔNIR is +21.12 % — approximately 4.2 % difference. For maize the gap is similar (+14.72 % vs +18.43 %, ~3.7 %). This arises because projected effective precipitation declines sharply under SSP585 end-of-century. Thus, while the demand-side driver (ETc) is the primary source of the climate-driven NIR increase, the supply-side decrease (effective precipitation) provides a secondary amplification that becomes dominant under the most extreme scenario.

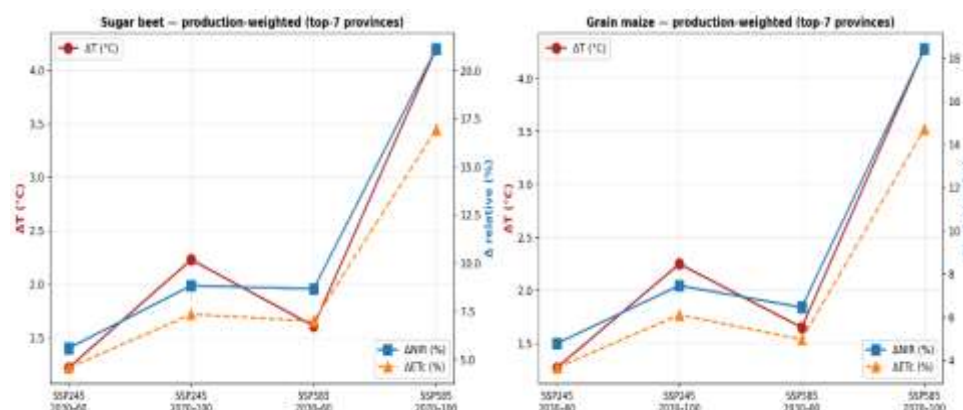


Figure 7. Production-weighted signal across the top seven producer provinces.

Offset ratio results in Table 2 indicate that 20 % modernization savings are sufficient under SSP245 and SSP585 near-term conditions, but become marginal or insufficient under SSP585 end-of-century, especially for sugar beet. In the top sugar-beet producer provinces, the production-weighted offset ratio under SSP585 end-of-century is 0.96 at 20 % saving, meaning that 20 % modernization savings fall slightly short of fully offsetting the climate-driven increase. At 30 % saving, the sugar-beet offset ratio rises to 1.43, indicating a clear full offset. For maize, the corresponding offset ratios are 1.13 at 20 % saving and 1.70 at 30 % saving.

Overall, the results show a clear scenario-dependent threshold. For both SSP245 and the near-term SSP585, moderate improvements in modernization are adequate to accommodate the anticipated rise in NIR due to climate factors. However, by the end of the century under SSP585, the system enters a higher demand phase where achieving a 30% water saving emerges as a more reliable goal for modernization, especially regarding sugar beet production

Table 2. Production-weighted results across the top seven producer provinces.

Period	Crop	Historical NIR (mm)	Future NIR (mm)	ΔT (°C)	ΔP (%)	ΔET_c (%)	ΔNIR (%)	Offset @ 20 %	Offset @ 30 %
SSP245 2030–2060	Sugar beet	794	838	1.22	–7.74	4.57	5.59	2.95	3
SSP245 2070–2100	Sugar beet	794	863.8	2.23	–13.31	7.35	8.83	2.34	2.9
SSP585 2030–2060	Sugar beet	794	862.4	1.61	–7.75	6.99	8.67	2.36	2.95
SSP585 2070–2100	Sugar beet	794	961.2	4.2	–29.37	16.94	21.12	0.96	1.43
SSP245 2030–2060	Maize	834	874.5	1.27	–9.63	3.66	4.79	2.97	3
SSP245 2070–2100	Maize	834	895.8	2.25	–13.39	6.12	7.47	2.68	2.99
SSP585 2030–2060	Maize	834	886.7	1.65	–6.67	4.97	6.46	2.82	3
SSP585 2070–2100	Maize	834	984.3	4.28	–28.78	14.72	18.43	1.13	1.7

4. CONCLUSIONS

The potential of irrigation modernization in offsetting increases in climate change-driven NIR for Türkiye's two strategic crops, sugar beet and maize, is investigated in this study. NEX-GDDP-CMIP6 climate projections, crop-specific K_c assumptions, effective precipitation estimates, and province-level aggregation for the top producer provinces are used in the analysis. The results show that future NIR differs significantly for different climate change scenarios. Under SSP245 and near-term SSP585 scenarios, projected NIR increases remain moderate and can be offset by water savings resulted from modernization. However, under SSP585 end-of-century scenario, results show that NIR for both crops increase substantially with production-weighted NIR increases reaching +21.12% for sugar beet and +18.43% for maize across the top-producing provinces.

The main policy implication is that a 20% modernization saving rate is not sufficient, particularly for sugar beet under a late-century climate change scenario (SSP585, 2070-2100). 20% savings fall slightly short of fully offsetting SSP585 end-of-century sugar-beet NIR increases, which can be offset by 30% savings. Konya is especially important because it dominates national production shares for both crops and lies exactly at the offset threshold (1.00) at 20% savings for sugar beet under the worst-case scenario. Therefore, in Konya 30% water saving should be aimed rather than 20%. It is important to note that these findings should be interpreted as field-scale offset potential of irrigation modernization under different climate change scenarios, not as guaranteed basin-scale water savings. In addition, modernization may actually increase the water use in agriculture, known as the rebound effect. The rebound effect implies the disappearance of the improvements in irrigation efficiency through expanded irrigation or selection of more water-intensive crops. Water allocation control and careful crop planning are needed in order to ensure that field-scale water savings scale up to the basin level.

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