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Assessment of agricultural adaptations to climate change from a water-energy-food nexus perspective

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ABSTRACT

Adapting agriculture to climate change without deteriorating natural resources (e.g., water and energy) is critical to sustainable development. In this paper, we first comprehensively evaluate six agricultural adaptations in response to climate change (2021–2050) through the lens of the water-energy-food (WEF) nexus in Saskatchewan, Canada, using a previously developed nexus model—WEF-Sask. The adaptations involve agronomic measures (early planting date, reducing soil evaporation, irrigation expansion), genetic improvement (cultivars with larger growing degree days (GDD) requirement), and combinations of individual adaptations. The results show that the selected adaptations compensate for crop yield losses (wheat, canola, pea), caused by climate change, to various extents. However, from a nexus perspective, there are mixed effects on water productivity (WP), total agricultural water (green and blue) use, energy consumption for irrigation, and hydropower generation. Individual adaptations such as early planting date and increased GDD requirement compensate for yield losses in both rainfed (0–60 %) and irrigated (18–100 %) conditions with extra use of green water (5–7 %), blue water (2–14 %), and energy for irrigation (2–14 %). Reducing soil water evaporation benefits the overall WEF nexus by compensating for rainfed yield losses (25–82 %) with less use of blue water and energy consumption for irrigation. The combination of the above three adaptations has the potential to sustain agricultural production in water-scarce regions. If irrigation expansion is also included, the combined adaptation almost fully offsets agricultural production losses from climate change but significantly increases blue water use (143–174 %) and energy consumption for irrigation while reducing hydropower production (3 %). This study provides an approach to comprehensively evaluating agricultural adaptation strategies, in response to climate change, and insights to inform decision-makers.

1. Introduction

Climate change can severely affect agriculture, given that farming activities are directly dependent on climatic conditions (Young et al., 2012), threatening global and local food security (Altieri and Nicholls, 2017). Rising temperatures can advance crop phenology and shorten growing cycles (Craufurd and Wheeler, 2009; Zabel et al., 2021). These effects are likely to reduce the total biomass and crop yield, which are widely reported in studies involving data observations, artificial warming experiments, and crop model simulations (Asseng et al., 2004; Zhao et al., 2017; Moore et al., 2021; Ullah et al., 2022). Furthermore, warmer temperatures intensify evapotranspiration and quickly deplete the soil water, which induces water stress, limiting the yield potential, as demonstrated by He et al. (2012) for spring wheat in Saskatchewan, Canada.

The threat to food security forces individuals and communities to respond and adapt to climate change (Thayer et al., 2020). Sustaining agricultural productivity requires targeted agronomic measures (e.g., changing planting date, changing fertilizer, irrigation, changing crop type, soil conservation, and crop diversification) and genetic improvements (Abid et al., 2015; Ladha et al., 2021), such as breeding cultivars with larger GDD requirements. However, adopting adaptation options over extended areas may cause unintended consequences due to associated externalities to other sectors (Thayer et al., 2020). The agricultural sector strongly connects with the water and energy sectors: 70 % of the world's freshwater withdrawals are attributed to agriculture and 30

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% of the world's consumed energy results from food production and supply chain. Furthermore, global projections show a 60 % increase in food demand, a 10 % increase in irrigation water withdrawals by 2050, and up to 50 % increase in energy consumption by 2035 (FAO, 2014). The WEF nexus approach helps identify the intersections, feedback loops, trade-offs, and synergies between water, energy, and food (Hoff, 2011; FAO, 2014; Abdelkader et al., 2018; Abdelkader and Elshorbagy, 2021; Wu et al., 2021; Wu et al., 2022). Therefore, this approach is useful and necessary to evaluate alternative adaptation strategies to sustainably manage the limited resources by improving the overall system efficiency which relies on reducing trade-offs while promoting synergies.

Some studies have addressed the effectiveness of adaptation strategies in maintaining agricultural production reliability (Zabel et al., 2021), while only a few studies analyzed the associated externalities to water or energy sectors in agricultural production. Rosenzweig et al. (2004) found cultivars adapted to projected climate change may have higher water demand than currently used varieties. Huang et al. (2018) indicated that extended irrigation likely reduces river discharge at the end of this century under the RCP2.6 scenario. Lee et al. (2020) adopted water footprint (m^3/tonne) and energy footprint (GJ/tonne) metrics as linkage indicators to paddy rice production and indicated that intermittent irrigation could save irrigation water as well as the associated energy use in the irrigation water supply but lower yield under climate change. Although the effects of different practical agronomic measures on crop yield have been widely addressed at field scales, the large-scale effects on agricultural production, water resources, energy consumption, and power generation under changing climate remain understudied. Moreover, many agricultural adaptation studies focus on irrigation (techniques and expansion), which is only feasible in water-abundant areas. Whereas only 20 % of the world's cultivated land is irrigated but accounts for 70 % of freshwater withdrawals (FAO, 2011), rainfed agriculture accounts for 80 % of the world's cultivated land and provides 60 % of agricultural production. Furthermore, climate change affects the conversion between irrigated and rainfed land due to uncertain water availability (Elliott et al., 2014). Thus, other agricultural adaptations that can enhance rainfed crop yield are also important, perhaps more robustly ensuring food security under changing climate and socioeconomic environments.

The effects of agricultural adaptations on the water-energy-food nexus, particularly under climate change, remain understudied. This study selected agricultural adaptation strategies that are most likely to be widely applied in practice in response to climate change. Moreover, we designed the combinations of the individual adaptation strategies and first applied a comprehensive WEF nexus modeling framework in the case of Saskatchewan, Canada to explore the sustainable ones that can benefit the agriculture sector without deteriorating water and energy resources. Specifically, this study analyzes crop growth responses (e.g., growing cycle length, first flowering date, biomass) to climate change and the effects of agricultural adaptations on crop production. The consequences of these adaptations to water and energy resources such as blue water use, energy consumption for irrigation, and hydropower production are further quantified at the provincial scale, where development plans and policy decisions are often designed and implemented (Wu et al., 2021).

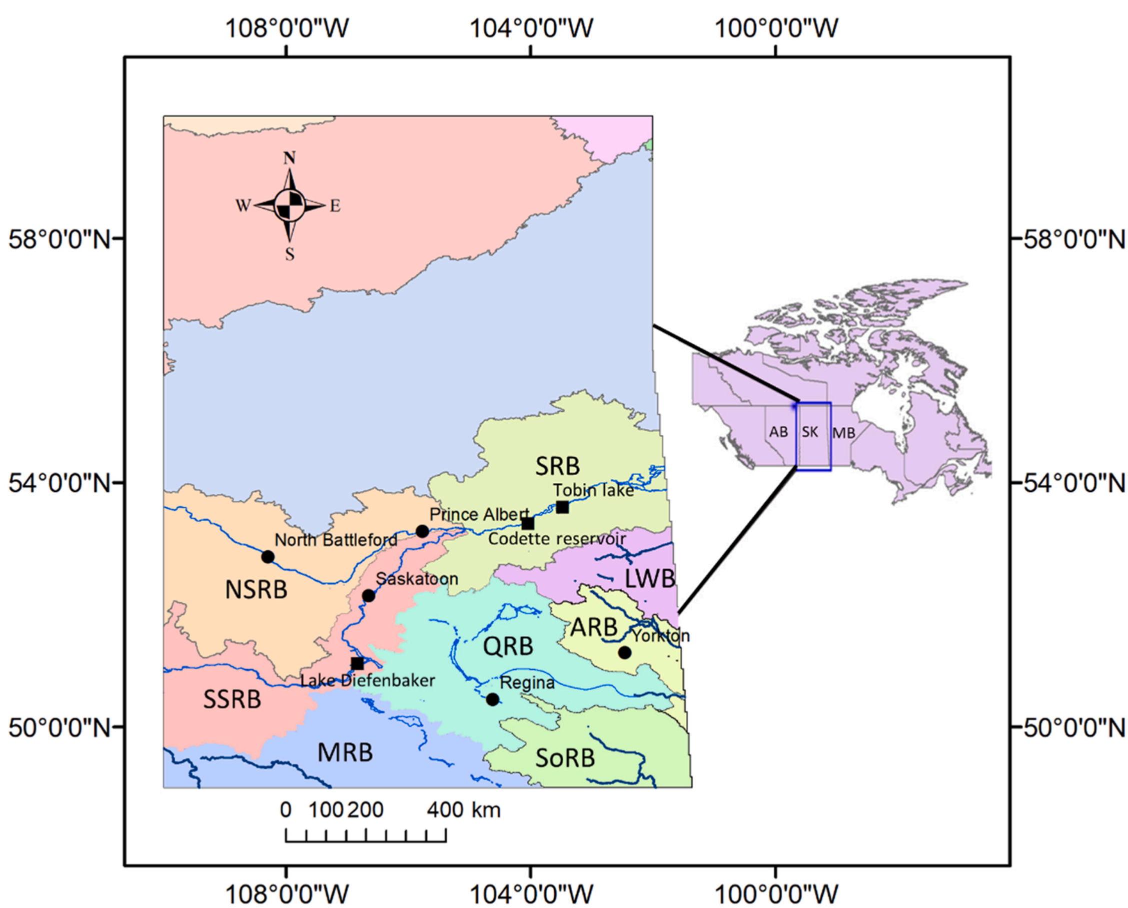

Fig. 1. Map of southern Saskatchewan, divided into river basins. SSRB—South Saskatchewan River Basin, NSRB—North Saskatchewan River Basin, SRB—Saskatchewan River Basin, ARB—Assiniboine River Basin, MRB—Missouris River Basin, QRB—Qu'Appelle River Basin, SoRB—Souris River Basin, LWB—Lake Winnipegosis Basin. AB—Alberta, SK—Saskatchewan, MB— Manitoba.

2. Methodology

2.1. Study area

Saskatchewan, one of the prairie provinces in western Canada, covers 651,036 km^2 and about 95 % of the provincial population lives in the southern half of the province (Kulshreshtha et al., 2012), where almost all of the agricultural activities occur. Southern Saskatchewan (Fig. 1), focused on this study, is a semi-arid area with an annual mean temperature of 0.6–3.9 °C and annual precipitation of 319–415 mm (Climate Atlas of Canada, 2019). Saskatchewan relies on an agricultural and resource-based economy and provides a consistent and reliable supply of food worldwide with international sales of $16.3 billion in 2020 (increased by 60 % since 2011), accounting for more than 55 % of total provincial exports. The province occupies large shares of the world food export market and is the world's largest exporter of peas (42 %), lentils (68 %), durum wheat (56 %), mustard seed (29 %), flaxseed (26 %) and oats (42 %) (Government of Saskatchewan, 2021). Therefore, the sustainability of agricultural production in this region plays an important role in global food security when the world population is estimated to increase to nine billion by 2050 (FAO, 2009).

Drought has frequently occurred throughout measured climate records in Saskatchewan. The province may experience further challenges in environmental and socioeconomic sectors from changing climate and water availability. The provincial transboundary rivers—The South Saskatchewan River (SSR) and the North Saskatchewan River (NSR), originating from the Rocky Mountains in the upstream province of Alberta, provide the most reliable water resource for irrigation and hydropower production. However, the local flows in southern Saskatchewan are highly variable, resulting in situations from droughts to floods (Saskatchewan Water Security Agency, 2012). Additionally, irrigated agriculture, along with oil and gas, potash, and other industries, are important growth sectors that need sufficient and sustainable water supplies, potentially resulting in competitive water use with municipal, power generation, recreational, and ecological sectors (Saskatchewan Water Security Agency, 2012).

2.2. Modeling framework

Fig. 2 shows the schematic of the proposed methodology in this study. The central part is the water-energy-food (WEF) nexus model that quantifies interactions among WEF sectors, driven by climate variables,

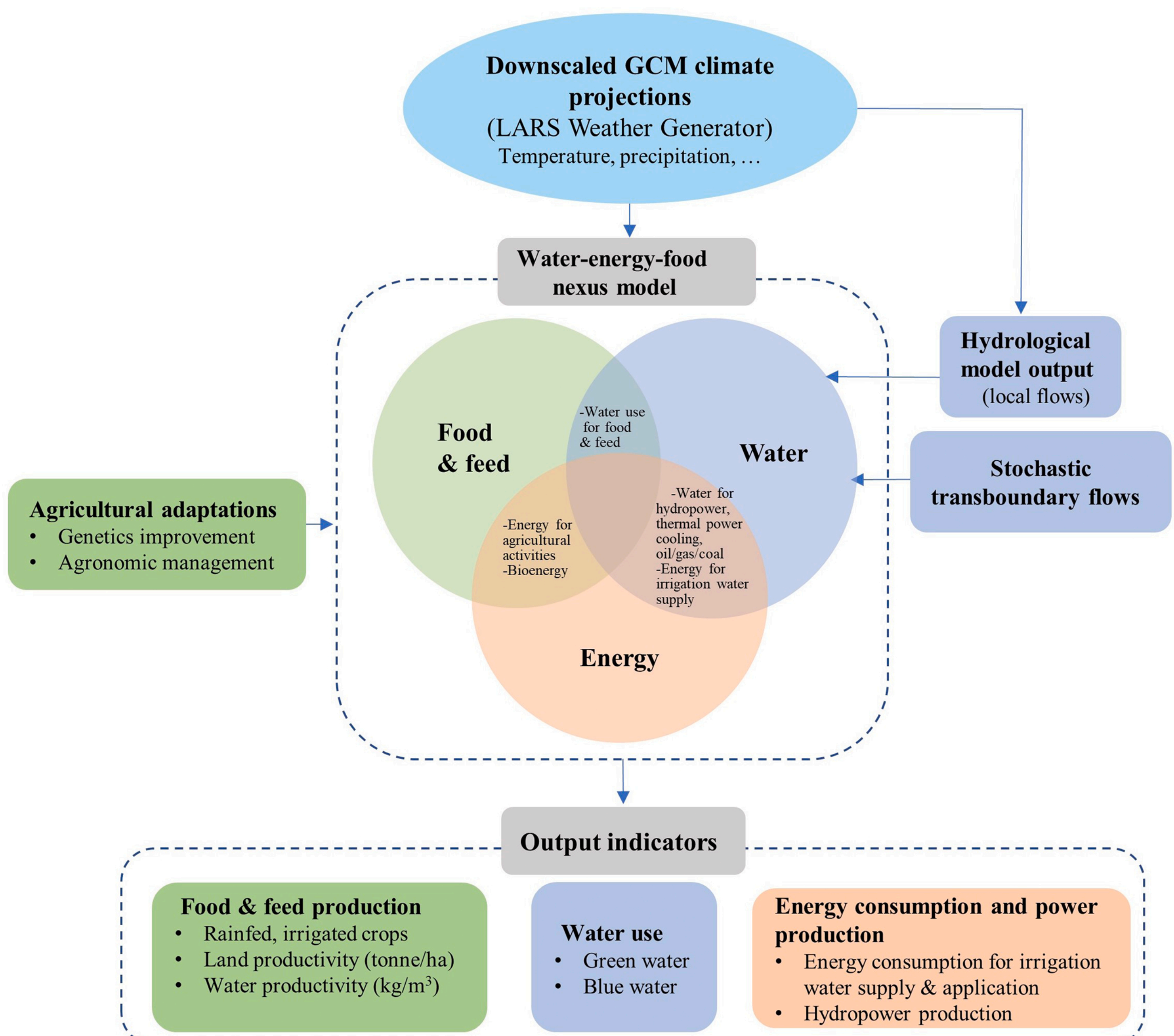

Fig. 2. Schematic of the methodology developed to evaluate the effects of agricultural adaptation strategies on food and feed production, water and energy use, and hydropower production.

surface flows coming from Alberta, and agricultural adaptation strategies. The previously developed WEF-Sask (built in STELLA 1.9; Wu et al., 2021) is such a nexus tool and was adopted in this study. WEF-Sask couples with climate change projections, a hydrological model—HYPR (Ahmed et al., 2020) (driven by climate scenarios to simulate future local flows), and stochastic transboundary flows (Nazemi et al., 2013) to simulate crop production, water demand/supply, energy consumption/production, and interactions among WEF sectors under plausible future hydroclimatic scenarios. Furthermore, the effects of agricultural adaptations on the WEF nexus were evaluated. Interactions among WEF sectors in Fig. 2 were quantified as follows: water use for food & feed was estimated by soil water balance, cropland area, and irrigation efficiency. Water use for energy production including thermal power cooling and crude oil/natural gas extraction) was calculated according to the water use coefficient (m^3/GJ) and energy production (GJ). Moreover, hydropower as clean energy was simulated by the water resource system in WEF-Sask. Water supply for irrigation consumes energy which was estimated based on the volume of irrigation water, total pressure head, and pump and motor efficiency. Energy consumption for food & feed production was estimated according to the energy input coefficient (e.g., MJ/ha) and cropland area. Food crops such as wheat and canola can be used to produce bioenergy, the demand of which was estimated based on the blending mandate (e.g., 25 % ethanol, 11 % biodiesel) and total gasoline/diesel demand in the transportation sector. Further, bioenergy demand was converted to feedstocks requirement (e.g., wheat and canola seed). The detailed quantifications of WEF interactions in WEF-Sask can be referred to Wu et al. (2021).

The LARS-5.5 weather generator was used to downscale and generate ensembles of climate realizations from general circulation models (GCMs) (Semenov and Barrow, 2002). Climate scenarios include a baseline climate (1986–2014) and four climate change signals (MIROC6-ssp126, HadGEM3-GC31-LL-ssp245, UKESM1–0-LL-ssp370, and FGOALS-g3-ssp585) from the Coupled Model Intercomparison Project Phase 6 (CMIP6) in 2021–2050, which were selected as representatives of the entire range of future climate projections (Wu et al., 2022). These four climate change scenarios projected from four GCMs (the British HadGEM3 and UKESM, the Chinese FGOALS, and the Japanese MIROC6) represent four Shared Socioeconomic Pathways (SSPs) and four radiative forcings (2.6, 4.5, 7.0, and 8.5Wm−2 by 2100). For each climate scenario, including the baseline, 100 stochastic realizations of daily time series were generated using the LARS-5.5 weather generator.

One hundred realizations of the critical water source to Saskatchewan— transboundary flows incoming from Alberta, were generated by the stochastic approach developed by Nazemi et al. (2013) based on the historical records during 1980–2010. The sequence number (from 1 to 100) of 100 realizations of a climate scenario corresponds to the same sequence number (from 1 to 100) of 100 realizations of the transboundary flow. Given five climate scenarios (baseline and four SSPs), 500 hydroclimatic runs were made in total. These hydroclimatic conditions were combined with each of the six agricultural adaptation strategies and no strategy, which are explained in the next section, resulting in a total of 3500 runs in this study. The details of hydroclimatic scenarios are described by Wu et al. (2022). This study first comprehensively assesses agricultural adaptation strategies to climate change from a water-energy-food nexus perspective. The output indicators in this study focus on rainfed and irrigated crop production, water productivity, green and blue water use in crop production, energy consumption for irrigation water supply and application, and hydropower production.

2.2.1. Crop production and agricultural adaptation strategies

The crop model in the previously developed WEF-Sask is derived from the classical Mitscherlich equation (Harmsen, 2000) and the FAO AquaCrop water-driven model (FAO, 2020) (Eq. (1); Wu et al., 2021). The Mitscherlich equation was used to capture the nutrient application effects on crop production, and a simplified AquaCrop version was mainly used to simulate crop yield response to meteorological variables. The details of the crop production simulation are described by Wu et al. (2021).

$$Y = (1 - e^{-c_1 \bullet N}) \bullet (1 - e^{-c_2 \bullet P}) \bullet f_{HI} \bullet \mathrm{HI_o} \bullet \mathrm{B} \quad (1)$$

where

Y—crop yield [tonne/ha],

N—nitrogen application rate [kg/ha/yr],

P—phosphorus as P_2O_5 application rate [kg/ha/yr],

c_1— crop-specific activity coefficient associated with N [-],

c_2— crop-specific activity coefficient associated with P [-],

f_{HI}— adjustment factor considering severe water and temperature stress [-],

HI_o—reference harvest index [-],

B— cumulative dry biomass production at crop maturity [tonne/ha].

In this study, we assume that nutrient management will be well implemented in the future, and the negative effects of nutrient application rate were ignored. Therefore, the crop yield is the product of the harvest index ($f_{HI} \bullet HI_o$) and biomass production, which is the same as in AquaCrop. Biomass (B; tonne/ha) accumulation during the crop growing cycle (emergence to maturity) is estimated from normalized biomass water productivity (WP^*; tonne/ha), and a sum of the ratio of the daily crop transpiration (Tr_i; mm/d) to the reference evapotranspiration (ETo_i; mm) (Eq. (2); FAO, 2020).

$$B = WP^* \bullet \sum Tr_i / ETo_i \quad (2)$$

The provincial scale yield calibration parameters include c_1, c_2, and other parameters related to soil water stresses, air temperature stresses, canopy development, biomass production, and yield formation. Apart from c_1 and c_2, other parameters were assigned the recommended values by Raes et al. (2018) based on extensive calibration/validation processes of AquaCrop and by Allen et al. (1998). Then, the Powell gradient search technique (Powell, 2009), built in STELLA 1.9, was applied to calibrate/validate the remaining crop parameters with the historical yield at the provincial scale (Statistics Canada, 2021a) by maximizing the Nash-Sutcliffe coefficient (NSE). The model performance is demonstrated in the supplemental file.

Variations of temperature and rainfall in the critical growth stage, such as the reproductive stage, are crucial to crop growth and production. Thus, the 10-day mean maximum/minimum temperature and accumulated rainfall under near-future climate change (2021–2050) during the crop growing season from May to September were calculated to help analyze crop responses to changing climate. Since crop yield is determined by biomass accumulation and harvest index (HI), indicators related to biomass and harvest index were selected. Biomass accumulation is related to the growing cycle length (emergence to maturity), water stress induced by high temperature and insufficient rainfall, and cold stress. Therefore, four indicators were selected to evaluate biomass: growing cycle length, transpiration without water stress (Tro), actual transpiration (Tr), and Tr/Tro. Severe water, heat, and cold stress affect pollination in the flowering period and, thus, the harvest index, which is mainly affected by severe water stress in the flowering period in this study. Therefore, the first flowering date was used to help evaluate the harvest index. The growth stage is determined by growing degree days (GDD) (Mkhabela and Bullock, 2012; Government of Saskatchewan, 2013).

The crop model was used to simulate the rainfed yield of 12 principal field crops—cereals (wheat, barley, oats, rye, and canary seed), oilseeds (canola, flaxseed, and mustard seed), pulses (chickpeas, lentils, and peas), and tame hay, and eight irrigated crops—cereals (wheat, barley), oilseeds (canola, flaxseed), potato, peas, forage crops (tame hay, corn silage). The provincial-scale yield (tonne/ha) of each crop is the sum of the weighted average yield from the eight basins using crop area as the weight. The crop area in each basin is estimated by aggregating the small agriculture census divisions according to the division area data

(Statistics Canada, 2021b) and the census subdivision map (Statistics Canada, 2019).

To cope with global warming problems in agriculture such as heat-induced water stress and shortened crop growing cycles, shifting the planting date may allow crops to grow in more favorable conditions (Wang et al., 2022), and selecting cultivars with long growing cycles increases biomass accumulation (Asseng et al., 2019; Zabel et al., 2021). However, these two strategies cannot guarantee higher water productivity and the adaptation of reducing non-productive water use (e.g., soil water evaporation) should be considered. Irrigation expansion is a traditional agricultural adaptation strategy but is limited by water availability (Schmitt et al., 2022). Furthermore, individual strategies have limited effects on crop production (Lorite et al., 2022) and therefore, combined strategies should be investigated. Considering the applicability to large scales, regional water availability, and plausible future climate conditions, six agricultural adaptation strategies, reflecting genetic improvement and agronomic management, were designed to cope with climate change:

- PD-15—advancing the planting date by 15 days to take advantage of the anticipated earlier spring thaw, alleviate water stress, and extend the length of the crop growing cycle.
- GDD+ 10%—10 % increase in growing degree days requirement in potential new cultivars to extend the length of crop growing cycle. This strategy increases the GDD requirement of a certain crop so that the crop needs more days to reach maturity, resulting in larger biomass accumulation and evapotranspiration (ET).
- E-50 %—reducing daily soil water evaporation by 50 % using agronomic methods, such as mulching, to reduce non-productive water consumption while promoting effective water use through transpiration.
- PGE— the combination of PD-15, GDD+ 10 %, and E-50 %.
- IE— irrigation expansion to improve food & feed production by withdrawing more blue water (from the current 50,000 ha to the potential of 250,000 ha in the Lake Diefenbaker area).
- PGEI— the combination of PGE and IE.

It is worth noting that whereas large irrigation expansion strategies (IE and PGEI) are often only feasible in water-abundant areas, other strategies mentioned above (PD-15, GDD+10 %, E-50 %, and PGE) can also be applied to water-scarce areas. Finally, we assessed the effects of these adaption strategies on crop yield, crop water productivity, green and blue water use in crop production, the associated energy demand for irrigation water supply, and hydropower production under various hydroclimatic conditions.

2.2.2. *Water productivity and crop water use*

Water productivity (WP, kg/m^3) of rainfed and irrigated crops is defined as the ratio of yield (kg/ha) to actual evapotranspiration (ET m^3/ha) during the growing cycle (Eq. (3); Fernández et al., 2020):

$$WP = \frac{Yield(kg/ha)}{ET(m^3/ha)}[\mathrm{kg}\Big/\mathrm{m}^3] \tag{3}$$

WP is important in agricultural and water management because higher WP indicates higher yield in water-limited conditions or water savings in water-sufficient conditions. The green and blue water terms (Mekonnen and Hoekstra, 2011) were used in this study because the source, storage, and use of the two water components are different. Blue water, stored in natural rivers, lakes, and aquifers, can be abstracted, diverted, transported, and stored in artificial reservoirs, and has a larger range of beneficial uses (e.g., irrigation, households, and industries) than green water, which is stored in the soil and primarily used in-situ for biomass growth (food, feed, or energy crops, and agroforestry) (Hoekstra, 2019). Therefore, it is necessary to distinguish between blue and green water when assessing agricultural adaptation strategies as trade-offs often occur in blue water among economic sectors while not in green water. In irrigated agriculture, blue water evapotranspiration (ET_b) is equal to the actual net irrigation, based on WEF-Sask output (Wu et al., 2021), and the green water evapotranspiration (ET_g) is equal to the actual water evapotranspiration (ET_a) minus ET_b (Hoekstra et al., 2011). Green water use (m^3) of all crops within the province is the accumulation of green crop water use over the rainfed and irrigated cropland. Blue water use (m^3) is the actual irrigation water supply simulated, by WEF-Sask model, based on crop soil water balance, cropland area, irrigation efficiency, and water availability. Irrigation water supply affects the water resource system in WEF-Sask and thus, hydropower production.

3. Results

3.1. *Climate change and crop responses*

Fig. 3 shows mean temperature and total rainfall on a 10-day scale from May to September to help analyze crop growth responses to climate in the future (2021–2050) compared to the baseline (1986–2014). Rainfed wheat growth in the South Saskatchewan River Basin (SSRB) shows an example to analyze the impacts of climate change and the adaptive effects of strategies on crop production. Fig. 4 demonstrates indicators closely related to biomass (growing cycle length, transpiration without water stress Tro, actual transpiration Tr, and Tr/Tro) and the indicator closely related to harvest index (the first flowering date). First of all, climate impacts on wheat growth under the no strategy (NS) scenario (white bars) are analyzed here. Fig. 4 shows a large wheat biomass reduction (~20 %) in SSRB under SSP126 and SSP370 due to the shorter growing cycle length and relatively higher water stress, which can be inferred by Tr and Tr/Tro. The actual transpiration Tr is limited by less rainfall from late June to August (Fig. 3) when the crop experiences a canopy development to maturity. Additionally, warmer temperature strengthens the atmospheric demand for evapotranspiration, which quickly depletes soil moisture and induces water stress. The model results show little impact of heat stress (e.g., maximum temperature >35 ℃) on the wheat harvest index, which is therefore considered to be only affected by severe water stress during the flowering period (early to mid-July under different SSPs). The severe water stress reduces the number of flowers (not pollinated) and the harvest index (fraction of yield to total biomass) under SSP126, SSP370, and SSP585 (Fig. 4). On the other hand, as seen in Fig. 4, SSP245 slightly increases the Tr/Tro ratio due to relatively high rainfall during the growing cycle compared to the baseline (Fig. 3). Moreover, the harvest index under SSP245 (Fig. 4) is not negatively affected because of the earlier first flowering date (11 days earlier than the baseline), which can help avoid severe water stress during the flowering period in mid-July.

As discussed above, warmer temperatures will reduce the growing cycle length and thus reduce biomass production. This reduction can be either exacerbated or alleviated by rainfall conditions in rainfed agriculture. Severe water stress may occur in July as almost all SSPs show decreased rainfall in this period in southern Saskatchewan, which will likely reduce the harvest index of those rainfed crops whose flowering period is in July, such as wheat. The earlier flowering period may help avoid severe water stress and maintain the harvest index.

Agricultural adaptation strategies alter the interactions between crops and the environment and affect crop production. Crop response to various adaptation strategies is also demonstrated in Fig. 4. The PD-15 strategy (green bars) can improve biomass accumulation compared to the no strategy scenario (white bars). This strategy allows crops to experience cooler temperatures, which prolong the growing cycle and may alleviate water stress induced by high temperatures (more atmospheric water demand) during the entire growing cycle. Additionally, the PD-15 strategy may slightly improve the harvest index compared to the no strategy scenario by alleviating severe water stress in the flowering period by advancing the first flowering date from mid-July to early

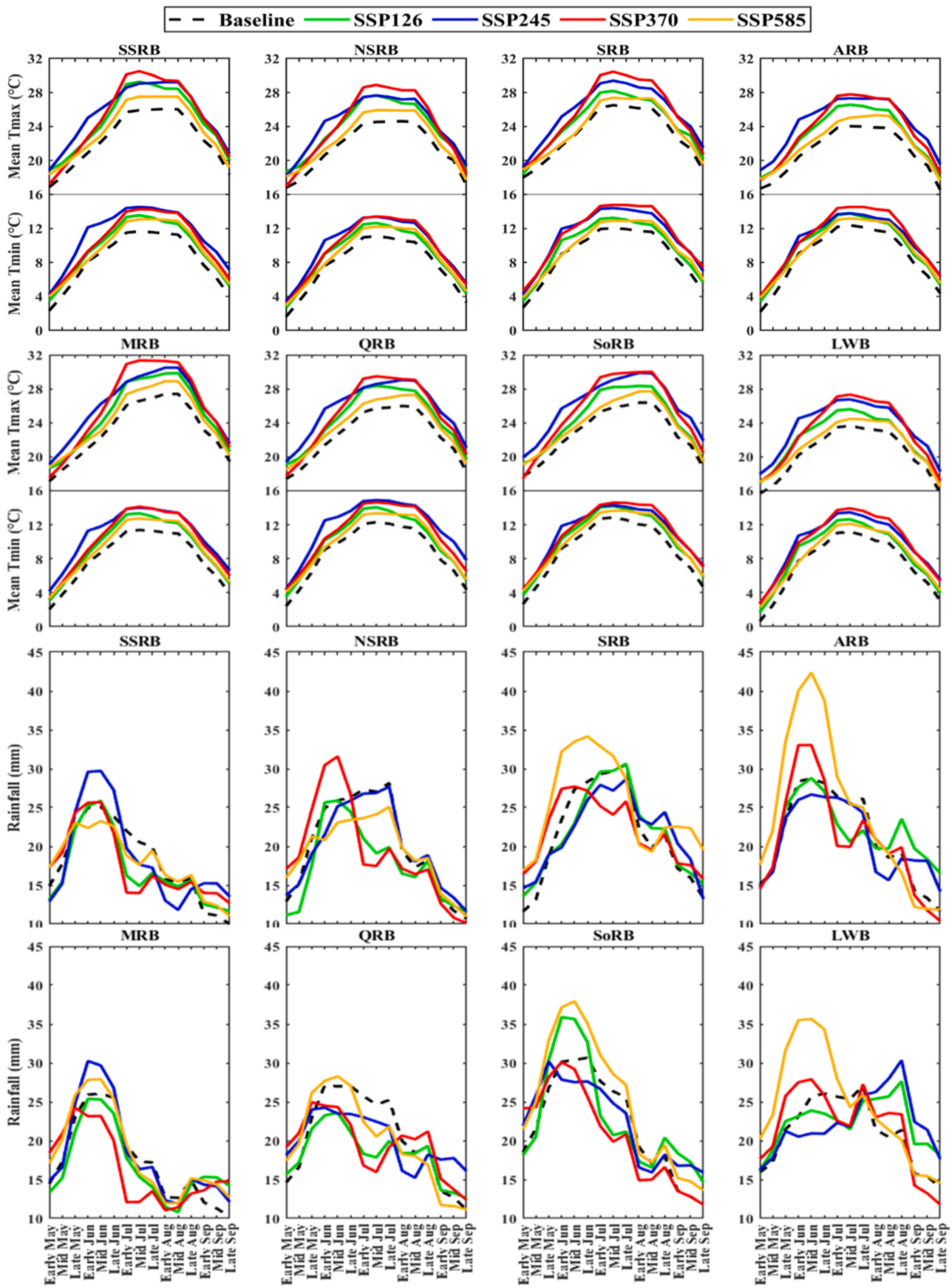

Fig. 3. 10-day mean maximum (T_{max})/minimum (T_{min}) temperature (℃) and accumulated rainfall from May to September under baseline (1986–2014) and future climate scenarios (2021–2050) in Saskatchewan's eight basins. The abbreviations of the basins are the same as in Fig. 1.

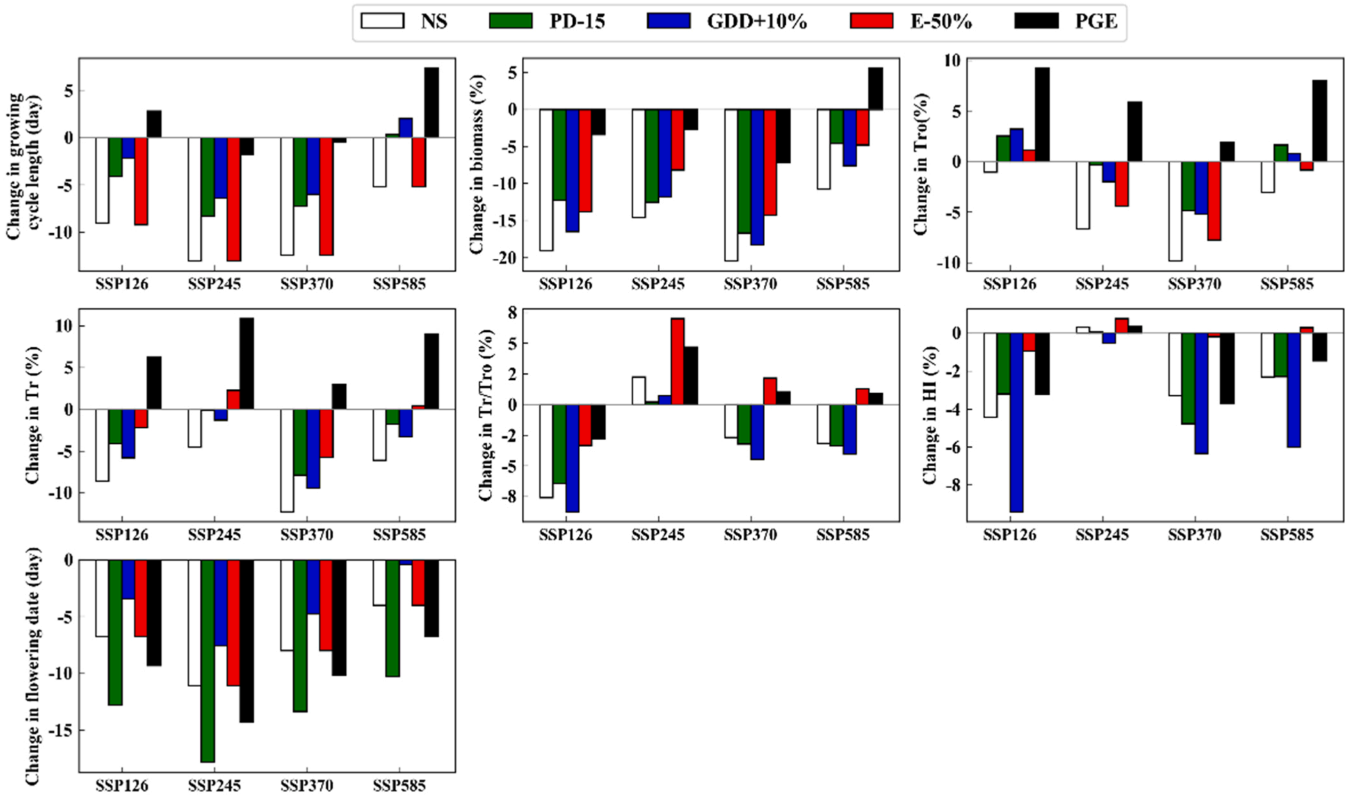

Fig. 4. Changes in 30-year averaged wheat growing cycle length, biomass, no water-limited transpiration (Tro), actual transpiration (Tr), Tr/Tro, harvest index (HI), and the first flowering date under climate change in 2021–2050 compared to baseline climate (1986–2014) with/without agricultural adaptation strategies. The negative values of growing cycle length indicate reduced days compared to baseline. The negative values of the flowering date indicate the number of days shifted earlier compared to the baseline.

July, such as under SSP126 (Fig. 4). The GDD+ 10 % strategy (blue bars) extends the growing cycle length and improves biomass accumulation compared to the no strategy scenario. However, this strategy likely postpones the first flowering date to mid-July and makes the crop experience severe water stress caused by worse rainfall conditions (Fig. 3), leading to a reduction in the harvest index. The E-50 % strategy (red bars) reduces non-effective soil water evaporation and alleviates water stress (higher Tr/Tro), particularly the severe water stress during the flowering period. Thus, more soil water is diverted to transpiration, improving biomass production and harvest index. The combined strategy PGE (black bars) takes advantage of the early planting date (PD-15), larger GDD requirement (GDD+10 %), and effective water use (E-50 %) and has the potential to largely compensate for the reduction in both biomass and harvest index resulting from climate change.

3.2. *Effects of adaptation strategies on crop yield, ET, and WP*

Wheat, canola, and peas are representative crops for cereals, oilseeds, and pulses, respectively, as described in Section 2.2.1, to show the impacts of climate change and adaptive strategies on crop yield and crop evapotranspiration (ET) in both rainfed and irrigated agriculture (Fig. 5). Crop yield is likely to be reduced due to climate change if no strategy (NS) is adopted (white bars). Warmer temperature shortens the growing cycle length of both rainfed and irrigated crops. Rainfed crops are also negatively affected by high temperature- and rainfall-induced water stress that affects biomass accumulation and even harvest index. In contrast, water was a non-limiting factor in biomass production and harvest index in irrigated crops with sufficient irrigation water supply. SSP370 and SSP126 have less rainfall than baseline starting from July in most basins (Fig. 3) and cause a 20–25 % reduction in the rainfed yield of wheat, canola, and peas. In contrast, a moderately warmer temperature combined with higher rainfall, such as SSP585 (Fig. 3), reduces the yield of wheat, canola, and peas by ~10 % (Fig. 5). The agricultural adaptation strategies (colored bars) potentially compensate for the rainfed crop yield losses caused by climate change to various extents. PD-15 and GDD+ 10 % individually can compensate for 0–60 % of rainfed yield (wheat, canola, peas) losses, while E-50 % shows more stable and effective compensation (25–82 %) of rainfed yield losses across all SSPs. The combined strategy PGE has a large potential to offset the negative impacts of climate change on crop yield, compensating for 45–87 % of rainfed yield (wheat, canola, peas) losses under SSP126, SSP245, and SSP370, even increasing the rainfed yield above the baseline under SSP585. Given that irrigation expansion has large-scale effects on blue water use and hydropower production, the PGEI strategy (combination of PGE and irrigation expansion) is not analyzed here but in Section 3.3 to show the nexus effects.

Climate change also reduces the irrigated crop yield under no strategy, primarily due to the shortened growing cycle length, which reduces seasonal light interception and photosynthesis (Islam et al., 2012). The strategies discussed above show different effects on irrigated crop yield. Given the negligible soil water stress, PD-15 and GDD+ 10 % are more effective in yield loss compensation (18–100 %). Unlike rainfed agriculture, although the E-50 % (red bars) strategy saves water from ineffective soil water evaporation, this strategy does not affect the yield of irrigated crops because no water stress occurs with or without the adoption of the strategy. Like rainfed agriculture, the PGE strategy effectively enhances irrigated crop yield and even exceeds the baseline climate level under SSP585.

Crop evapotranspiration (ET) during the growing cycle is affected by the magnitude of the daily reference ET rate, the length of the growing cycle, and soil water availability. Rising temperature increases the vapor pressure deficit and intensifies transpiration and soil water evaporation

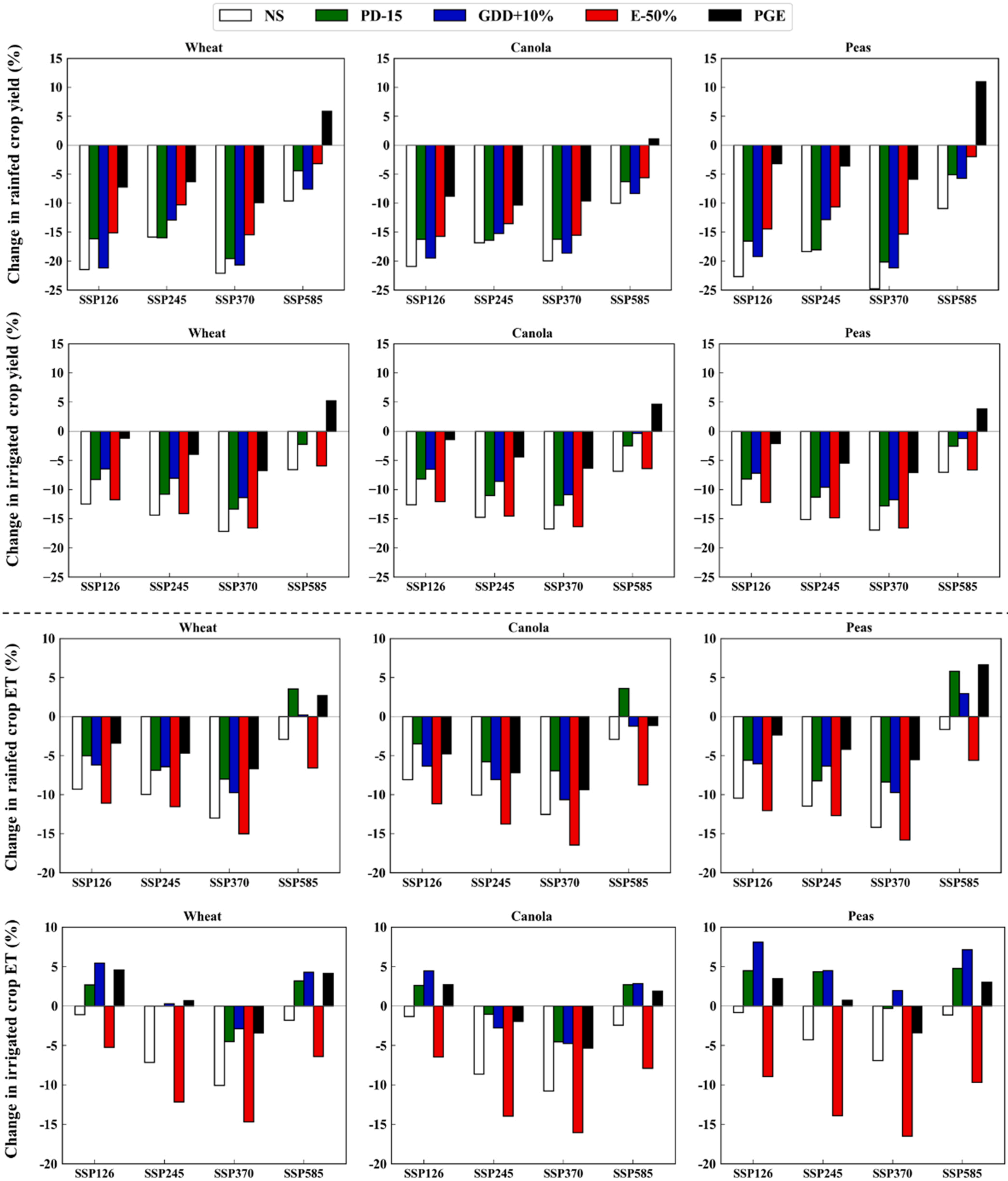

Fig. 5. Percentage change in 30-year averaged rainfed and irrigated crop yield and ET under climate change in 2021–2050 compared to baseline climate (1986–2014) with/without agricultural adaptation strategies. Bars show the averaged change values of 100 realizations.

rate to meet the atmospheric water demand. Higher atmospheric water demand also potentially causes water stress for crops. Along with shortened growing cycle due to a warmer climate, yield reduction may occur while ET increases. Fig. 5 shows climate change likely reduces ET in both rainfed and irrigated agriculture under the no strategy scenario (white bars), mainly due to the shortened growing cycle and variable soil water availability, although the daily reference evapotranspiration (ETo) or the evaporation power is intensified. Adaptation strategies affect ET in different ways. The PD-15 and GDD+ 10 % strategies extend the growing cycle and, thus, increase ET compared to no strategy. In contrast, the E-50 % strategy reduces soil water evaporation and thus, always reduces ET below no strategy level. The PGE strategy that combines the PD-15, GDD+ 10 %, and E-50 % also increases crop ET above no strategy level in rainfed and irrigated agriculture. Unlike rainfed agriculture, the PD-15 and GDD+ 10 % strategies increase ET of irrigated crops (e.g., wheat, canola, peas) at a larger level, even higher than the baseline level, because water stress is not a limiting factor for ET.

Fig. 6 shows the effects of adaptation strategies on water productivity (WP) of rainfed and irrigated crops under climate change. The WP concept helps evaluate the effective or productive use of water under alternative adaptation strategies, aiming to achieve "more crop per drop", which is of great importance in both agricultural production and water resource management. Higher WP values mean higher yield in water-limited conditions or water savings in water-sufficient conditions. Climate change likely reduces crop WP because rising temperature increases vapor pressure deficit and atmospheric water demand. Adaptation strategies show various impacts on WP. Given that PD-15 and GDD+ 10 % extend the growing cycle, both crop yield and ET increase and thus, WP is either increased or decreased under these two strategies compared to the no strategy scenario. The E-50 % strategy largely improves crop WP (even exceeding the baseline level such as under SSP585) compared to no strategy level in both rainfed and irrigated agriculture. In addition, the PGE strategy also largely improves WP, indicating that the combination of adaptation strategies containing an effective water use strategy (e.g., E-50 %) likely enhances WP.

3.3. Effects of adaptation strategies on total crop production and water and energy use

Agricultural adaptation strategies are essential to maintain food and feed production; meanwhile, they also bring externalities as agricultural activities are inevitably connected to water and energy sectors. Fig. 7 shows the average annual total food and feed production, water use and energy use for irrigation, and provincial hydropower production during 2021–2050 under climate change with/without adaptations. Two additional strategies are also assessed: irrigation expansion (IE) that benefits the rural economy and the combined strategy PGEI (combination of PD-15, GDD+ 10 %, E-50 %, and IE). Total water use in crop production is differentiated into green and blue water use in million cubic meters (MCM), given the difference between green and blue water in storage and use (Hoekstra, 2019). Blue water is the actual irrigation water use, restricted by water availability. The mean values of 100 realizations of these indicators under SSPs and baseline (dashed lines) were compared.

Fig. 7 shows that all individual strategies improve crop production moderately compared to no strategy level; however, neither can alone fully offset crop production losses from climate change. In contrast, the combination of possible strategies—the PGEI strategy is robust to climate change scenarios assessed in this study to almost fully offset the food & feed production losses from climate change, even exceeding the baseline crop production by 12 % under SSP585. The SSP370 scenario slightly reduces agricultural production by only 2 % with the PGEI strategy. Similarly, the PGE strategy also significantly compensates for the loss of food and feed production, even exceeding the baseline production under SSP585 (7 %). This result suggests that the combination of agronomic measures and genetic improvements to crop varieties has the potential to largely or even fully offset the agricultural production losses from climate change in those semi-arid areas where large irrigation expansion is not feasible due to water scarcity.

The agricultural adaptation strategies show various impacts on water and energy use in agriculture. As seen in Fig. 7, compared to the no strategy scenario, the E-50 % strategy moderately reduces the green and blue water use and energy consumption while effectively improving crop production, whereas the individual strategies PD-15 and GDD+ 10 % moderately increase the use of green water (5–7 %), blue water (2–14

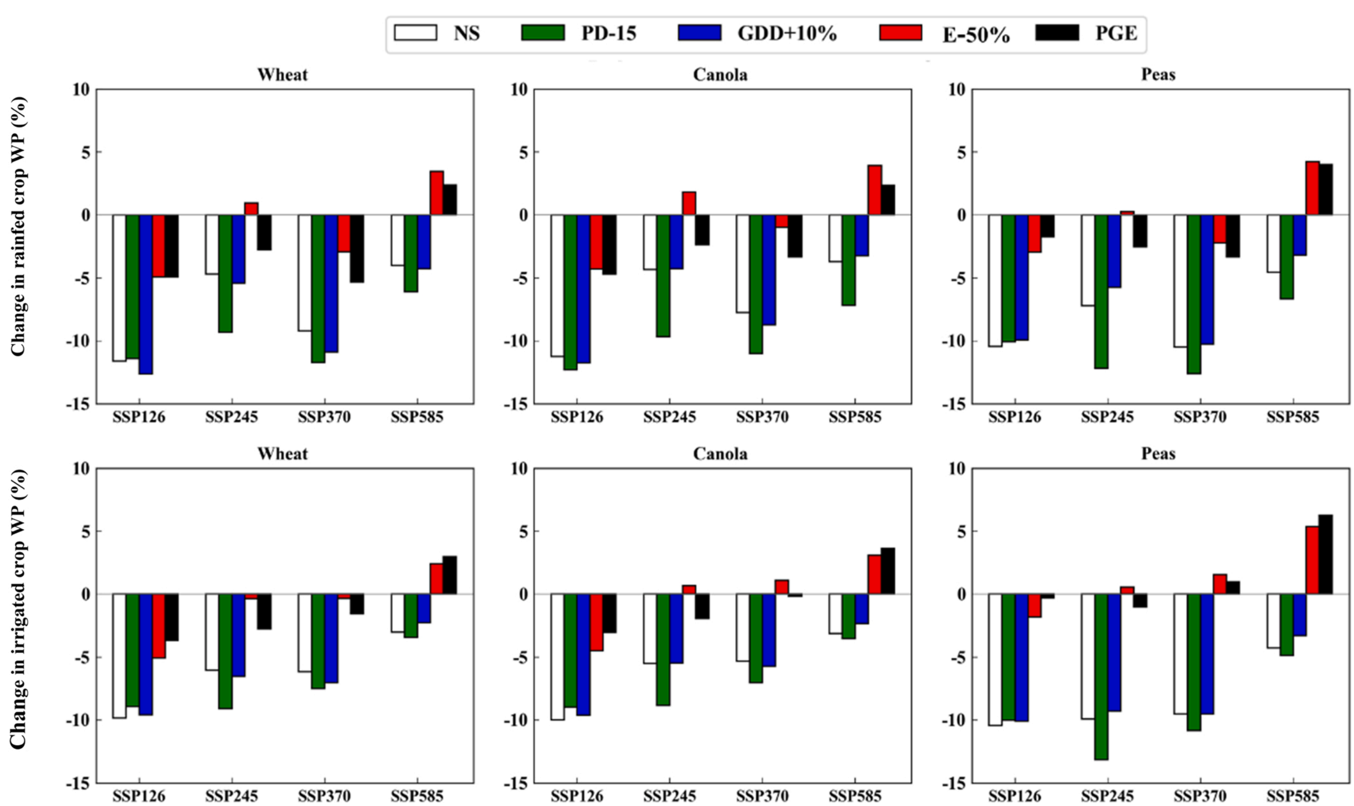

Fig. 6. Percentage change in 30-year averaged rainfed and irrigated crop water productivity under climate change in 2021–2050 compared to baseline climate (1986–2014) with/without agricultural adaptation strategies. Bars show the averaged change values of 100 realizations.

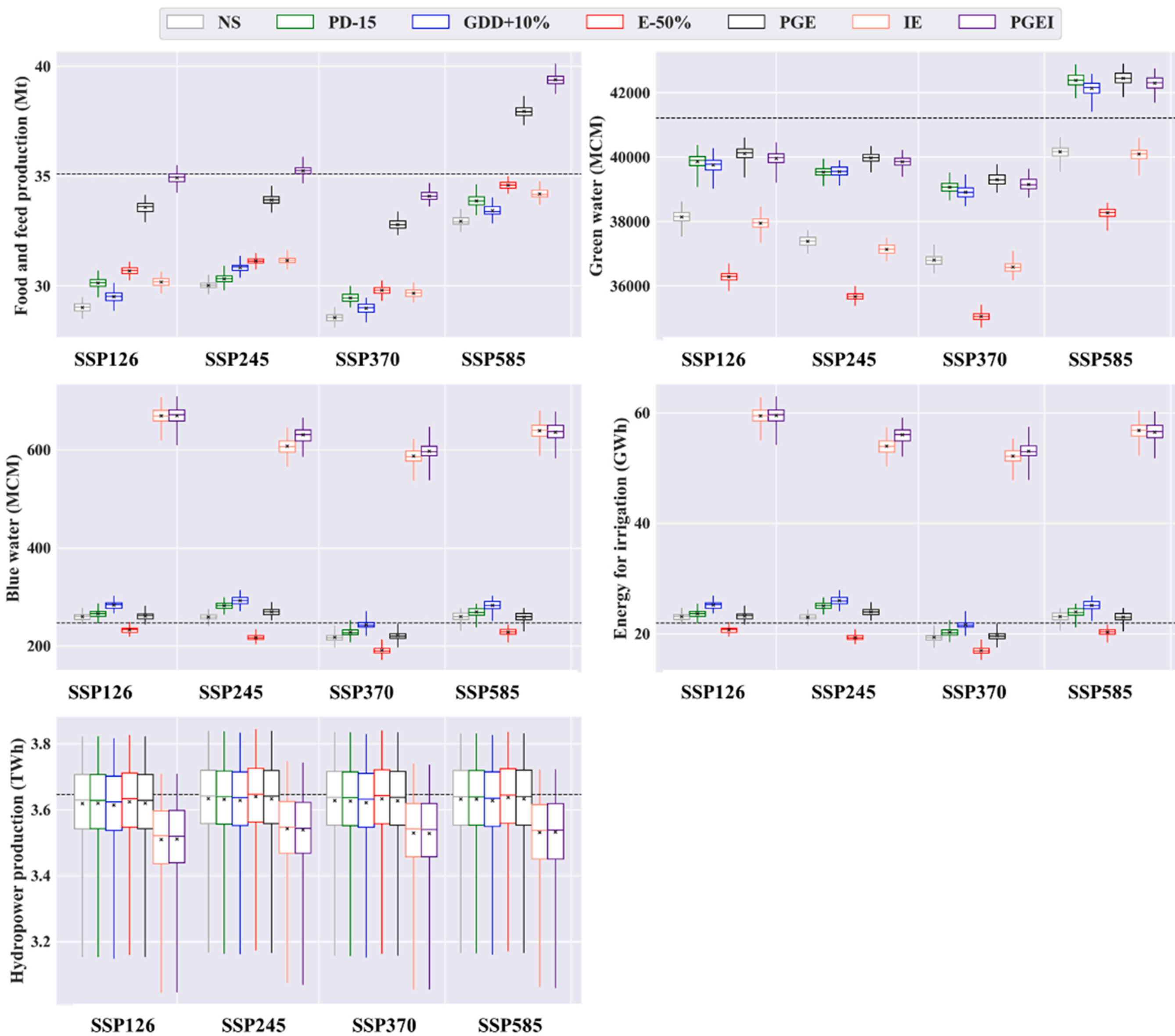

Fig. 7. Annual food and feed production, water and energy use in crop production, and hydropower production under projected hydroclimatic conditions in 2021–2050 with/without agricultural adaptation strategies. The dashed lines show the mean values of 100 realizations under baseline climate during the 1986–2014 period. The boxplots represent the interquartile range (IQR) values, with the median shown as the solid line within the box and the whiskers showing the maximum/minimum values of 100 realizations.

%), and energy for irrigation (2–14 %). Owing to involving irrigation expansion (IE), the PGEI strategy significantly increases blue water use (also the associated energy use for irrigation water supply) by 143–174 %. Overall, strategies involving effective water use, such as reducing soil water evaporation (E-50 %, PGE) can effectively improve agricultural production with much less or even no extra use of blue water and energy compared to strategies involving large irrigation expansion (IE, PGEI).

Given the hydropower-irrigation trade-off in Saskatchewan (Hassanzadeh et al., 2016; Wu et al., 2021), agricultural adaptations may affect hydropower production, and this potential issue is analyzed here. It is worth noting that the variations of hydropower production in Fig. 7 predominantly result from the stochasticity of the inflows from Alberta. As seen in Fig. 7, irrigation expansion alone (IE) or combined with other strategies (PGEI) obviously reduces hydropower production, while the remaining strategies show slight impacts. Despite increasing total agricultural production by 4 % (1.1–1.3 Mt), irrigation expansion alone increases energy use for irrigation by 135–170 % (31–36 GWh) and reduces hydropower production by 3 % (92–109 GWh) compared to the no strategy scenario under various climate scenarios, indicating a significant increase in energy demand while reducing renewable energy supply. Therefore, large irrigation expansion requires cautious evaluation and management, particularly under future uncertainties. Other agricultural adaptations without significantly intensifying water use trade-offs should also be considered. For example, the E-50 % strategy alone shows slight synergetic benefits by reducing energy use for irrigation (with the existing irrigated area) by 10–16 % (2–4 GWh) while increasing hydropower production by 0.15 % (5 GWh) compared to the no strategy scenario. In addition, the PGE strategy has little impact on energy use for irrigation water supply and hydropower production.

4. Discussion

4.1. Agricultural adaptations affecting the water-energy-food nexus and sustainable development

Sustainable agriculture is critical to achieving many Sustainable

Development Goals (SDGs), such as ending poverty and zero hunger (FAO, 2015) and ensuring human well-being without deteriorating the surrounding ecosystems' capacity, environmental integrity, and social-economic functions (FAO, 2018). Agricultural adaptations are key to reducing the negative impacts of climate change on food production. Previous adaptation assessments focus on the agriculture sector (Abid et al., 2015; Ladha et al., 2021) while ignoring the broader-scale influences on other sectors, which may directly or indirectly affect other SDGs, such as clean energy and water (FAO, 2015). Given that food, energy, and water are fundamental resources for human welfare, the important linkages and feedback loops among them need to be identified and quantified. In other words, "nexus" thinking and management become important in agricultural sustainability practices. To the best of our knowledge, this is the first study to evaluate agricultural adaptations individually and in combination under a wide range of climate conditions through the lens of the WEF nexus. This complex and challenging endeavor was conducted by applying a comprehensive modeling framework that couples a WEF nexus model, a hydrological model, and climate change projections (Wu et al., 2021).

Irrigation is a widely used measure for enhancing food production by withdrawing blue water to supplement the water deficit when green water does not meet crop water requirements. Expanding irrigation offers opportunities to offset the reduction in food production due to water stress, which may be exacerbated by global warming (higher atmospheric water demand). However, irrigation expansion is not always feasible due to freshwater limitations, which might even cause reverting cropland from irrigated to rainfed management under future climate change (Elliott et al., 2014). In regions where there is potential for expanding irrigation, such as Saskatchewan (by 400 %), whereas total crop production increases by 4 %, large amounts of blue water withdrawal require extra energy (by 135–170 %) for irrigation water supply while reducing hydropower production (by 3 %), putting pressure on clean energy transition and climate change mitigation.

Instead of seeking more blue water supply through irrigation expansion, which also requires considerable investments in irrigation infrastructure, adaptations promoting food production by expanding green water use with no extra or relatively low cost merit attention. Unlike blue water, which has a wide range of uses, green water is primarily used in situ for biomass growth (Hoekstra, 2019), avoiding competition over water between different sectors. In addition, given that rising temperature accelerates crop development and shortens the growing cycles (Asseng et al., 2004; Zhao et al., 2017) as shown in Fig. 4, naturally, measures that extend growing cycles and increase biomass accumulation, as well as the yield, are more adaptive to global warming. Examples of such adaptations are advancing the planting date or selecting crop varieties with larger growing degree days (GDD) requirements, where more green water is used for crop production in both rainfed and irrigated conditions. Irrigation water demand will also rise, but slightly, compared to large irrigation expansion (Fig. 7).

Adaptations that target more use of either green or blue water (e.g., irrigation, advancing planting date, and selecting varieties with larger GDD requirement) to meet crop transpiration and atmospheric water demand may not increase crop water productivity (WP). Reducing non-effective water use, i.e., soil water evaporation, allows to divert more water to productive transpiration, promoting yield increase in rainfed crops, saving water in irrigated crops, and increasing WP under both conditions. van Donk et al. (2010) suggested that 65–100 mm of more irrigation water is required to grow the extra 1.6 tons/ha of corn yield benefited from crop residue management. In our case study, reducing soil evaporation also shows synergetic benefits by saving energy consumption for irrigation by 10–16 % (2–4 GWh) while slightly increasing hydropower production by 0.15 % (5 GWh) compared to the no strategy scenario. Furthermore, reducing soil water evaporation combined with other adaptations except irrigation expansion allows higher resilience of the food production system under climate change without diminishing blue water resources and hydropower production (Fig. 7).

4.2. Policy implications

As discussed above, the WEF nexus analysis reveals trade-offs and synergies and therefore has the potential to promote policy coherence in actual resources management. Take for example Saskatchewan in which strategies for multiple systems including natural systems (land, water, forests), communities, infrastructure, and economy (Government of Saskatchewan, 2017) have been made to improve the resilience of the province to climate change. However, current sectoral policies lead to trade-offs. For instance, in the energy sector, Saskatchewan has proposed plans to double its renewable electricity capacity by 2030 to cut greenhouse gas emissions in electricity production by 40 % below the 2005 level. Nevertheless, large irrigation expansion, which is currently underway in the Lake Diefenbaker area, reduces hydropower production and thus, impedes renewable energy expansion. Therefore, there is a need to build shared principles and values as well as a consistent understanding of nexus issues (Weitz et al., 2017) among actors such as farmers and hydropower enterprises to achieve policy coherence. Moreover, multiple adaptations, particularly those that can bring synergetic benefits (e.g., reducing soil evaporation) or avoid significant deterioration in water and energy sectors, should also be considered.

4.3. Limitations and potential future research

This study is a step forward toward comprehensively evaluating various agricultural adaptation strategies from the water-energy-food nexus perspective under a wide range of future hydroclimatic conditions. However, some limitations exist in this study: (i) The model does not capture the process of rising temperatures affecting photorespiration rates and photosynthetic efficiency and ignoring crop yield quality, and (ii) this study evaluates agricultural adaptation strategies at a provincial scale; however, proper strategies often vary across locations. For example, the optimal planting date for a crop depends on the meteorological conditions and often varies from place to place. Therefore, future studies should (i) evaluate the effects of climate change on crop photosynthetic efficiency and crop yield quality using modeling methods to help identify adaptation strategies, such as breeding heat-resistant crop varieties; and (ii) design, optimize, and evaluate agricultural adaptation strategies from a nexus perspective under finer spatial resolutions, such as agricultural divisions, to capture the heterogeneity of meteorological conditions.

5. Conclusions

The effects of agricultural adaptation strategies on the water-energy-food nexus under climate change have been evaluated based on a comprehensive framework coupling a WEF nexus model—WEF-Sask, a hydrological model—HYPR (simulating local flows), stochastic transboundary flows, and climate change projections. Our findings show that reducing soil evaporation (E-50 %) brings synergetic benefits to the overall WEF nexus by improving rainfed crop yield and water productivity, reducing or maintaining nearly historical blue water use and energy consumption for irrigation, and slightly increasing hydropower production. The PGE strategy, a combination of advancing the planting date (PD-15), growing cultivars with higher requirements of growing degree days (GDD+10 %), largely compensates for climate change-induced crop yield losses under both rainfed and irrigated conditions and effectively increases water productivity while not deteriorating water resources and hydropower production. Thus, the PGE strategy has the potential in sustaining agricultural production in water-scarce regions where large irrigation expansion is infeasible. If irrigation expansion (IE) is also included, the PGEI strategy (combination of PD-15, GDD+10 %, E-50 %, and IE) almost fully offsets crop production losses; however, this strategy significantly increases blue water use (also the associated energy use for irrigation water supply) by 143–174 % and reduces provincial hydropower production by 3 % under various climate change scenarios. Therefore, large irrigation expansion should be well assessed and cautiously managed, and multiple adaptations should be applied to achieve sustainable agriculture. This study shows that WEF nexus analysis has the potential to promote policy coherence by revealing trade-offs and synergies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2023.108343.

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