European Journal of Agronomy 172 (2026) 127855

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Model projections indicate substantial decrease in yield stability for summer crops in Switzerland, but less so for winter crops

Márcio dos Reis Martins *, Pierluigi Calanca

Agroscope, Climate and Agriculture Group, Zurich 8046, Switzerland

ARTICLE INFO

Keywords:
Climate scenarios
Cropping systems
Drought
Global warming
Mechanistic modeling
Mitigation scenarios

ABSTRACT

Yield stability is critical to farm income and food security. The impact of future climate change on crop yields and yield stability was assessed for Swiss croplands, focusing on four key regions: Eastern Jura, Western Plateau, Central Plateau, and Northeastern Plateau. Projections for eight different crops were performed using the process-based model DayCent and downscaled climate scenarios for Switzerland (CH2018 framework), using outputs of 12 climate models for the scenario without mitigation measures (RCP 8.5) and for the scenario with stringent mitigation (RCP 2.6). Change in yield stability was gauged by means of relative change in the standard deviation (SD) of inter-annual yield fluctuations between 1981–2010 (reference) and 2045–2074 (mid-century). The average yields of most crops tend to increase as a result of warming and elevated CO_2 levels, particularly under the RCP 8.5, although associated with a considerable divergence within the ensemble of climate models. On the other hand, a substantial increase in yield variability, *i.e.* decline in yield stability, is consistently projected for all summer crops under the RCP 8.5, with changes that are higher in magnitude than for cereal winter crops. The Central Plateau is projected to experience the greatest decline in yield stability for summer crops, with SD under RCP 8.5 increasing by over 50 % for maize, 40 % for potatoes, 60 % for soybean and 25 % for sugar beet. Elevated CO_2 levels tend to overall alleviate this negative impact, especially for maize, for which the projected increase in SD in Central Plateau lessens from 50 % to 20 %. Overall, our results emphasize the contrast between summer and cereal winter crops in terms of yield stability, which can guide future strategies for adapting cropping systems to climate change.

1. Introduction

Yield stability will be of extreme importance for the economy of farms and the consumer market in the coming decades. For the farmers, the higher yield stability can ensure steady incomes (Mottaleb et al., 2013; Reidsma et al., 2010). For the food supply, it can mitigate the prices volatility (Lobell et al., 2011) that could favor future food security efforts (Headey and Martin, 2016; Su et al., 2023; Thomasson, 2025), particularly in a scenario with low global food stocks associated with projected increasing demand due to population growth (Wright, 2011; Ghosh et al., 2024). Globally, the variability in staple crop yields is increasing at a concerning pace (Ray et al., 2015; Vogel et al., 2019), which has a significant impact on the food market (Chatzopoulos et al., 2020), as indicated by increased frequency of food price spikes (Gbegbelegbe et al., 2014; Porter et al., 2014). The temporal variability in food commodities production can amplify the impact on price variability due to the inelastic nature of the market for agricultural products (Barr et al., 2011; Orm, 2023; Rao, 1989), *i.e.* even relatively small changes in the amount of supply or demand will have a strong effect on product prices. In Europe, recent summer droughts have been identified

Abbreviations: BAS, Basel/Binningen weather station; BER, Bern/Zollikofen weather station; cCO_2, current CO_2 level; CH2018, climate change scenarios for Switzerland; DayCent, Daily Century model; DOK, German acronym for "Dynamisch, Organisch, Konventionell"; eCO_2, elevated CO_2 level; GHG, greenhouse gas; KLO, Zurich/Kloten weather station; K_{sat}, saturated conductivity; NCCS, National Centre for Climate Services; NPP, net primary productivity; PAY, Payerne weather station; PTF, pedotransfer function; QM, quantile mapping; RCP 2.6, Representative Concentration Pathway with stringent mitigation measures of GHG emissions; RCP 8.5, Representative Concentration Pathway with no abatement of GHG emissions; SD, standard deviation; SOC, soil organic carbon; TR, transpiration rates; β, parameter controlling CO_2 effect on plant productivity or transpiration; Δ_{min}, maximum amount of the volumetric soil water content that can be lost below permanent wilting point..

* Corresponding author.
E-mail address: marcio.dosreismartins@agroscope.admin.ch (M. dos Reis Martins).

https://doi.org/10.1016/j.eja.2025.127855
Received 17 June 2025; Received in revised form 11 September 2025; Accepted 12 September 2025
Available online 16 September 2025

as a major driver of crop yield losses with impact on food market (Ciais et al., 2005; Schmitt et al., 2022; Vogel et al., 2019; Webber et al., 2018), at the example of the 2018 event, which drastically reduced the supply of agricultural products (Deutsche Welle, 2018). To deal with these problems, future projections of the impact of climate change on yield and yield variability can provide strategic support for mid-century food market trends in line with the policy planning for the future of food sector in European countries, such as the Agriculture and Food Climate Strategy 2050 for Switzerland (FOAG, 2025) and the Farm to Fork Strategy for European Union countries (European Commission, 2024).

There is no doubt that climate variability and the occurrence of extreme climatic events have had significant impacts on yield stability in the recent past, explaining, on a global scale, between 18 % and 43 % of yield variability, depending on the crop (Vogel et al., 2019). Similarly, a study including maize, rice, wheat and soybean showed that climate variability explains more than 60 % of the yield variability observed over the period 1979–2008 in the major agricultural regions of the world (Ray et al., 2015). In addition, the same study showed that, with respect to maize, temperature variation accounted for more of the yield variation in colder than in warmer regions. Along the same line, Iizumi and Ramankutty (2016) found that in 9 %–22 % of the harvested area of maize in the world, yield variability significantly increased over the 1981–2010 period.

Looking ahead, other studies suggest that crop production will remain sensitive to climate variability (*e.g.*, White et al., 2021; Qiao et al., 2022). However, they also indicate that climate change will impact yield stability differently, depending on crop (its resistance and resilience with respect to unfavorable growing conditions), and other environmental factors affecting crop growth (*e.g.*, soil quality). Techniques to improve crop performance through breeding could help stabilizing yields, though (Stella et al., 2023).

Given this background, assessing how future climate could affect yield stability is of paramount importance for developing measures of adaptation at regional levels (Qiao et al., 2022). Although farmers are aware of the potential for climate-induced crop yield losses, the future impact of climate variability can be so high that it does not allow for basic adaptation solutions. Insurance products against drought-induced losses can buffer the economic negative impact of yield variability and are generally well accepted by farmers in response to extreme events (Mao et al., 2025; Wang et al., 2022). However, adaptive actions such as those based on insurance products and other technologies (*e.g.*, increased storage capacity) have limits in terms of effectiveness in response to risk level (Berkhout and Dow, 2023; Dow et al., 2013). The situation is made more challenging by climate change, because this is causing a transition from systematic to non-systematic risks (Steen et al., 2023).

In Switzerland, as in other European countries, both winter and spring or summer crops are cultivated and included in crop rotations. A basic question for future adaptation of cropping systems to climate change is whether these two crop types will respond differently to climate change in terms of yield stability. In terms of average yields, it has been overall indicated that maize, a typical summer crop, can be more negatively impacted by climate change than wheat (Cammarano and Tian, 2018; Webber et al., 2018). However, the impact on yield stability of summer crops in comparison to winter crops has, so far, received little attention. An important factor that could potentially affect yield stability is the response of different crop types to increasing atmospheric CO_2 levels, although there are studies suggesting that varying CO_2 levels would only explain a small fraction of the yield variability (Ostberg et al., 2018, Schauberger et al., 2017). While C3 crops, such as wheat, potatoes, and sugar beet, have the capacity to increase both water use efficiency and photosynthesis rates, C4 crops, such as maize, benefit almost solely from improved water-use efficiency (Ainsworth and Long, 2005, 2021; Darwin and Kennedy, 2000) because current atmospheric CO_2 levels already exceed 400 ppm and the saturation point of their photosynthetic response to increasing CO_2 (*cf.* p. 178 in Larcher, 2003).

For Switzerland, understanding and projecting yield stability under future climate is critically important, as this could represent a challenge for food supply, especially in view of the fact that the self-sufficiency degree of Switzerland in plant-based food is far below 100 % (FOAG, 2024a, SWISSINFO, 2025), as for other European countries (Kaufmann et al., 2022), and that the country has to import *ca.* 50 % of the needs for calories supply (Ritzel and von Ow, 2023). As agricultural land per capita is declining in Switzerland (Ritzel and von Ow, 2023), ensuring yield stability is of paramount importance to maintain or even increase the self-sufficiency in crop-based products.

The aim of this study was to assess future climate change impact on crop yields and yield stability in the main cropland regions in Switzerland. To frame future climate projections we used the official, downscaled climate scenarios for Switzerland available at the time of writing (CH2018, 2018), as provided by the Swiss National Centre for Climate Services (NCCS), the federal network that mandated the study to support informed decision-making on climate-related issues (NCCS, 2025). The CH2018 climate projections are based on the EURO-CORDEX ensemble of regional climate simulations, which project climate change for alternative scenarios ranging from no abatement of greenhouse gas (GHG) emissions (Representative Concentration Pathway 8.5, or RCP 8.5 for short) to adoption of stringent mitigation measures (RCP 2.6) to prevent warming from reaching 2°C above pre-industrial levels (CH2018, 2018). For each of these RCPs, we used outputs of 12 climate models considered in the CH2018 framework. To gauge the effects of climate change, we compared two time windows, *i.e.* 1981–2010 (reference) and 2045–2074 (mid-century), with corresponding atmospheric CO_2 levels of 360 ppm on average over the 30 years considered in the former and 443 ppm (RCP 2.6) or 602 ppm (RCP 8.5) in the latter case. The following questions were addressed in the study: (i) How will climate change affect average yields and yield stability of winter crops (*i.e.* crops growing in autumn-winter-spring) *versus* summer crops (*i.e.* crops growing in spring-summer) at mid-century? (ii) How do changes in average yields and yield stability depend on the choice of emission scenarios (*i.e.* with and without mitigation measures)? And (iii) What role will mid-century CO_2 elevation play in crop responses to climate change in terms of average yields and yield stability?

2. Material and methods

To conduct the analysis, we defined four regions accounting for most of the arable crop area of Switzerland (Fig. 1). The definition of these for regions was based on Schüepp and Gensler (1980) and WSL (2023) and reflects to the one adopted by NCCS for discussing the regional implications of climate change.

We simulated crop yields using the process-based model DayCent, version DD17centEVI (Hartman et al., 2019). This model has efficiently simulated biomass yields, especially in cases where there is no severe N limitation for plant growth (Grant et al., 2016; Qian et al., 2019; Sansoulet et al., 2014). It accounts for carryover effects, related in particular to soil water and nutrient availability, which makes the model useful for modeling complex multiple-species crop rotations (Adler et al., 2018; Iqbal et al., 2018). In the present study, we used parameter values obtained from an extensive calibration procedure using inverse modeling based on observed data from long-term field experiments at various sites in Western Europe, which was reported in details in a previous study (*cf.* Martins et al., 2022). As in the present investigation we were not interested in examining effects arising from site and crop-specific characteristics, we used, for each crop type, only average parameter values, which we considered as representing generic crop types.

In DayCent, the daily maximum plant productivity is controlled by soil water content, temperature, solar radiation, and availability of nutrients (N, P, and S). The model considers that, without limitation related to water, temperature and nutrients status, the plant productivity is primarily a function of the daily solar radiation, genetic

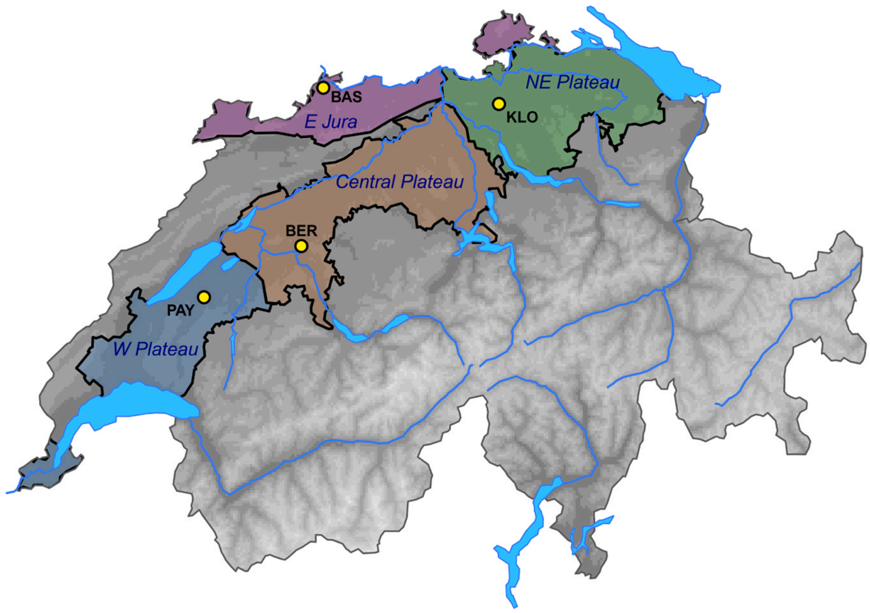

Fig. 1. The four cropland regions in Switzerland considered in the present study. The yellow dots indicate representative locations with weather stations, for which downscaled outputs from the climate models of the CH2018 framework were used. BAS, Basel-Binningen; BER, Bern-Zollikofen; KLO, Zurich-Kloten; PAY, Payerne (*cf.* Details in Table 1).

Table 1
Weather stations selected in the present study for climate projections in the four most important cropland regions in Switzerland.

Weather station	Abbreviation	Latitude	Longitude	Elevation (m a.s.l.)	Cropland region
Basel / Binningen	BAS	47°32'28.1"N	7°35'00.7"E	316	Eastern Jura
Payerne	PAY	46°48'41.7"N	6°56'32.9"E	490	Western Plateau
Bern / Zollikofen	BER	46°59'26.7"N	7°27'50.6"E	553	Central Plateau
Zürich / Kloten	KLO	47°28'46.6"N	8°32'09.5"E	426	Northeastern Plateau

maximum potential given by a crop specific radiation use efficiency, and scalars quantifying the effects of air temperature, soil water content, shading by vegetation, phenological stage, and atmospheric CO_2 level on growth (Hartman et al., 2019).

Two key effects of the CO_2 increase are represented in the model. The first effect is the increase in plant productivity through stimulation of photosynthesis and reduction in photorespiration. This effect is stronger in C3 than C4 crops (Hocking and Meyer, 1991). The second key effect is to reduce stomatal conductance and therefore decrease plant transpiration (Katul et al., 2009; Walker et al., 2021). The combined effect of increased photosynthesis and decreased transpiration improves the water use efficiency (Katul et al., 2009; Walker et al., 2021). In DayCent, the response to elevated atmospheric CO_2 level is modelled as a logarithmic function (Gifford, 1979, 1980; Goudriaan, 1992; Goudriaan et al., 1985), as presented in the Eq. (1) below:

$$NPP_e = NPP_c \times \left\{1 + \beta \times \ln\frac{[CO_2]_e}{[CO_2]_c}\right\} \tag{1}$$

where *NPP* is net primary productivity, β is a parameter ranging from 0 and ~0.7, depending on crop, $[CO_2]$ is the atmospheric CO_2 level; the subscripts "*e*" and "*c*" specify, respectively, elevated and control CO_2 environments. Eq. (1) was parameterized based on a meta-analysis of observations of change in different plant parameters from classical FACE experiments (Ainsworth and Long, 2005; Cure and Acock, 1986) (*cf.* Fig. S1). The effect of elevated CO_2 on transpiration rates (*TR*) is modelled in the same way, as shown in Eq. (2) below, but in this case β was set to −0.33 for all crops, based on observed results from the above-mentioned studies (Fig. S1).

$$TR_e = TR_c \times \left\{1 - 0.33 \times \ln\frac{[CO_2]_e}{[CO_2]_c}\right\} \tag{2}$$

Soil characteristics required on input by DayCent (Table 2) were specified using data provided by the Swiss Soil Competence Center (Stumpf et al., 2021) or by applying pedotransfer functions according to Saxton and Rawls (2006) and Wösten et al. (1999). Default values were used for the fraction of roots and for the maximum amount of the volumetric soil water content that can be lost below wilting point (Δ_{min}).

For model initialization (spinup), we specified management based on historical information from the literature (Bürgi, 2016). We assumed that agriculture began following the clearing of deciduous forests and

Table 2
Soil properties used as DayCent inputs for the simulations of crop production.

Soil property	Data source for regional simulations	Reference
Sand, clay, silt, pH, SOC[1]	Soil maps produced by the Swiss Competence Center for Soil	Stumpf et al. (2021)
Bulk density	PTF[2] based on land use, SOC content and texture	Wösten et al. (1999)
Field capacity, wilting point, K_{sat}^3	PTFs based on bulk density, SOC content and texture	Saxton and Rawls (2006)
Fraction of roots[4], Δ_{min}^5	Default values provided by DayCent developers	Hartman et al. (2019)

[1]Soil organic C, it is used in DayCent simulations for prediction of soil temperature; [2] Pedotransfer function; [3] Saturated hydraulic conductivity; [4] Fraction of roots in soil layer (sum of fractions from different layers = 1.0); [5] Maximum amount of the volumetric soil water content that can be lost below the wilting point – it is used to estimate the minimum achievable water content in the soil (minimum soil water content = wilting point – Δ_{min}).

progressed through distinct stages aligned with advancements in farming technology, with gradual increases in N inputs, crop diversity and yields. The historical periods considered were: pre-agricultural revolution (1500–1750), agricultural revolution (1751–1850), agricultural intensification (1851–1950), and agricultural modernization (1951–1980). Further details of this approach for model initialization were described by Necpalova et al. (2018) and Martins et al. (2022).

For simulations during the modern period (1981–2099), a standardized management scheme was applied, adopting a 9-year crop rotation scheme based on information from long-term field experiments conducted in Switzerland and neighboring countries (Martins et al., 2022). The most important source of management information regarding crop sequence and management practices, including sowing (date), soil preparation (type and date) and harvesting (type and date), was the conventional treatment from the so-called DOK experiment (German acronym for "Dynamisch, Organisch, Konventionell"). This experiment, installed in 1977 and located in Therwil, Switzerland, was designed to compare organic and conventional systems based on different fertilization strategies (Mäder et al., 2002; Mayer et al., 2015). The basic crop rotation consisted of a crop sequence represented by grass-clover ley (2 years), maize, sugar beet, winter wheat, rapeseed, winter barley, soybean and potatoes. Although in Switzerland more than 70 % of the area cultivated with maize is used for silage (FOAG, 2024b), in our simulations we considered only grain production for this crop, assuming that in the future there will be a greater demand for grain production for human consumption and less for animal feed (European Commission, 2024; FOAG, 2025). In line with this, we included soybean in the simulations. Soybean actually represents less than 1 % of the cropland area (FAOSTAT, 2025; FOAG, 2024b), but we assumed its share will increase in the future to cover the demand for oilseeds and as a major source of plant protein for human nutrition (Keller et al., 2024). For all crops, simulations were carried out considering only rainfed conditions.

Because of the year-to-year variability in weather conditions, nine different rotations were included in the simulations to allow for varying interactions between crops and weather in different years. These nine rotations were defined based on the above-mentioned scheme by introducing a sequential one-year shift, *i.e.*:

- *Rotation 1:* …–A–B–C–D–E–F–G–H–I–…
- *Rotation 2:* …–B–C–D–E–F–G–H–I–A–…
- *Rotation 3:* …–C–D–E–F–G–H–I–A–B–…
- Rotation *i:* …
- *Rotation 9:* …–I–A–B–C–D–E–F–G–H–…

where, for the sake of simplicity, we use letters A to H to represent the different crops.

All the different management schedules were run for each region, for each RCP and for each climate model. For the fertilization, we used the automatic fertilization mode encoded in DayCent, considering no limitation of nutrients (N, P and S) for the crop growth over the simulation period. As for the weather, we used the "extra drivers" mode of the model, which requires the following variables: precipitation, minimum and maximum air temperatures, relative humidity, solar radiation, wind speed. Data for the latter were taken from the official climate scenarios for Switzerland (the so-called CH2018 scenarios), considering the DAILY-LOCAL datasets, which provide transient daily data for the period 1981–2099 for localities with representative meteorological stations in Switzerland (CH2018 Project Team, 2018). For each of the four study areas, a weather station was chosen to represent the climatic characteristics driving crop growth (Fig. 1, Table 1).

The CH2018 climate scenarios were originally derived from the EURO-CORDEX projections, which were performed using a combination of global and regional climate models (EURO-CORDEX, 2024; Giorgi et al., 2009), and the local data were produced using a 30-year reference period (1981–2010) for bias correction and a downscaling procedure based on quantile mapping (QM) (CH2018 Project Team, 2018). Further details can be found in CH2018 (2018) and Feigenwinter et al. (2018). The projections of change in mean monthly precipitation and mean monthly air temperature based on the CH2018 framework for each of the selected stations are presented in the Fig. 2.

To cover the lower and upper end of possible future climate developments, in our study we selected climate change scenarios representing the RCP 2.6 and RCP 8.5 emission pathways, but neglected the intermediate scenarios representing the RCP 4.5. In this respect, we note that in the context of climate change impact assessments, it is not uncommon to find studies in which the modeling efforts are concentrated on more critical scenarios (*e.g.*, Chou et al., 2014; San José et al., 2016). For each RCP, we included 12 model chains, as listed in Table S1 in the Supplementary Material. As for the temporal variation of atmospheric CO_2 levels, we considered the projections as indicated by Meinshausen et al. (2011) for each RCP. These are shown in Fig. S2, also in Supplemental Material.

Two time slices were selected to study changes in average crop yields and interannual yield variability: (*i*) 1981–2010 as the reference period and (*ii*) 2045–2074 as the mid-century period. We used the inter-annual standard deviation (SD) as a measure of yield variability (and hence indicator of yield stability), considering the relative change in SD from the reference to the mid-century period to quantify the impacts of climate change.

3. Results

The absolute values of average yield for the reference period (1981–2010) show that among the four regions, the Central Plateau is the one with the highest modeled values for grass-clover ley and summer crops (grain maize, potatoes, soybean, sugar beet) (Table 3), which clearly reflects the higher precipitation values in this region (Fig. 2). On the other hand, the Eastern Jura region had the highest modeled yields of winter crops in the reference period (Table 3), which is associated with average monthly temperatures *ca.* 1.5°C above those observed in the other three regions (Fig. 2). As seen in Table 3, overall, we simulated higher crop yields for the reference period than recorded in the national yield statistics available from the Food and Agriculture Organization (FAOSTAT, 2025). This result can be understood referring to the assumption of no nutrient limitation for crop growth as a basis for our simulations.

Regarding the SD of crop yields in the reference period, it is seen that, with exception of grass-clover ley, the Central Plateau also stands out for having lower values than in other regions (Table 3), *i.e.* presenting the highest crop yield stability, in spite being one of the two regions with highest year-to-year variability in monthly precipitation (*cf.* precipitation SD in Fig. S4). This result indicates a dampening effect related to higher precipitation levels in this region (Fig. 2), *i.e.* higher mean precipitation levels reducing the effects of variability in precipitation on yields.

The projected changes in average yields and yield SD for the different crops (Figs. 3 and 4) illustrate both the overall shift (*i.e.* displacement from zero, upwards or downwards of the ensemble median), as well as the associated uncertainties (*i.e.* vertical extent of the underlaying box, representing the range between the 5th- and 95th-quantile of the ensemble). For spatial visualization, the median projections of the changes for both average yields and SD of yields are also displayed as maps (Figs. 5 and S3). These latter figures indicate that, overall, the differences between crops, as well as differences across the considered production regions, depended on the choice of emission pathway.

Considering in more detail the results, we note that for RCP 2.6 there is a tendency toward increased yields, particularly in soybean and all the winter crops (rapeseed, winter barley and winter wheat), if compared to maize, potatoes, and sugar beet (Figs. 3, 5 and S3). As the difference in CO_2 levels between reference and future timeframe is small for RCP 2.6, as seen in Fig. S2, the same is true for the effects of elevated CO_2

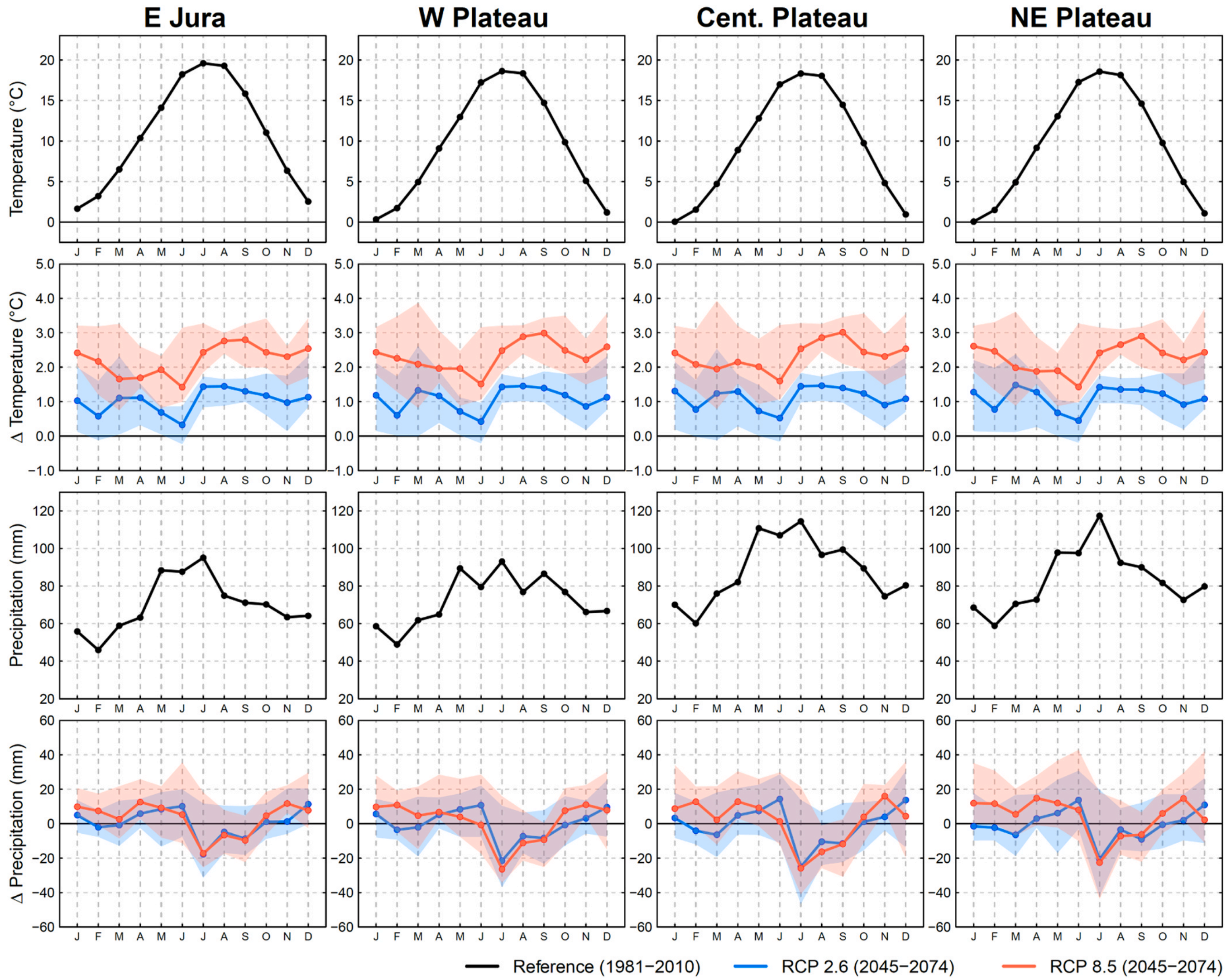

Fig. 2. Monthly values of precipitation, temperature in the reference period (1981–2010) and corresponding changes (Δ) in the mid-century (2045–2074) under different climate scenarios in four cropland regions in Switzerland. The scenarios are derived from an ensemble of 12 climate models of the CH2018 framework. The shaded areas represent the 90 % quantile range of the uncertainty from the ensemble of climate models.

Table 3
Mean ± standard deviation (SD) of the modeled crop yields (Mg DM ha^{-1}) in the reference period (1981–2010) in different cropland regions in Switzerland. Each value represents the median of the ensemble based on the outputs of 12 climate models.

Region	Grass-clover ley	Grain maize	Potatoes	Rapeseed	Soybean	Sugar beet	Winter barley	Winter wheat
Modeled								
Eastern Jura	13.00 ± 1.41	9.84 ± 1.40	9.04 ± 1.09	4.37 ± 0.48	2.86 ± 0.46	18.10 ± 2.02	8.74 ± 0.66	7.94 ± 1.09
Western Plateau	12.95 ± 1.46	9.79 ± 1.49	9.01 ± 1.18	4.07 ± 0.55	2.79 ± 0.47	18.08 ± 2.41	8.52 ± 0.80	7.22 ± 1.15
Central Plateau	13.55 ± 1.47	10.37 ± 1.04	9.40 ± 0.83	4.25 ± 0.46	3.02 ± 0.35	18.84 ± 1.69	8.70 ± 0.60	7.40 ± 0.96
Northeastern Plateau	13.33 ± 1.42	9.97 ± 1.27	9.17 ± 0.97	4.13 ± 0.48	2.88 ± 0.42	17.95 ± 2.06	8.54 ± 0.75	7.17 ± 1.11
Observed (FAOSTAT, 2025)								
Switzerland	n.a.*	8.56 ± 1.20	7.84 ± 0.87	2.95 ± 0.29	2.73 ± 0.37	14.64 ± 1.95	5.73 ± 0.67	5.70 ± 0.50

*n.a.: not available.

concentrations on crop yields (*cf.* light blue bars and dark blue bars in Fig. 3). On the other hand, considering the yield projections for the RCP 8.5 emission scenario, it is seen that winter crops differ from summer crops in two ways (Fig. 3). The first is a clear tendency of winter crops to benefit from rising atmospheric CO_2 in future (Figs. 3, 5 and S3). Among winter crops, the highest increments under elevated CO_2 levels are observed for winter wheat, ranging from 24 % to 30 %, and for rapeseed, ranging from 29 % to 32 % (Figs. 3, 5 and S3). In contrast, typical summer crops cultivated in Switzerland (maize, sugar beet and potatoes) usually presented little increase in mean yields under elevated CO_2 levels, or even a decrease in drier regions (*viz.* Western Plateau and Eastern Jura) when CO_2 are kept at current levels (Figs. 2, 3, 5 and S3). The exception among summer crops was soybean, for which there is a projection reaching 29 % increase when CO_2 elevation is considered under the RCP 8.5 (Figs. 3 and S3).

The second aspect distinguishing summer and winter crops is the

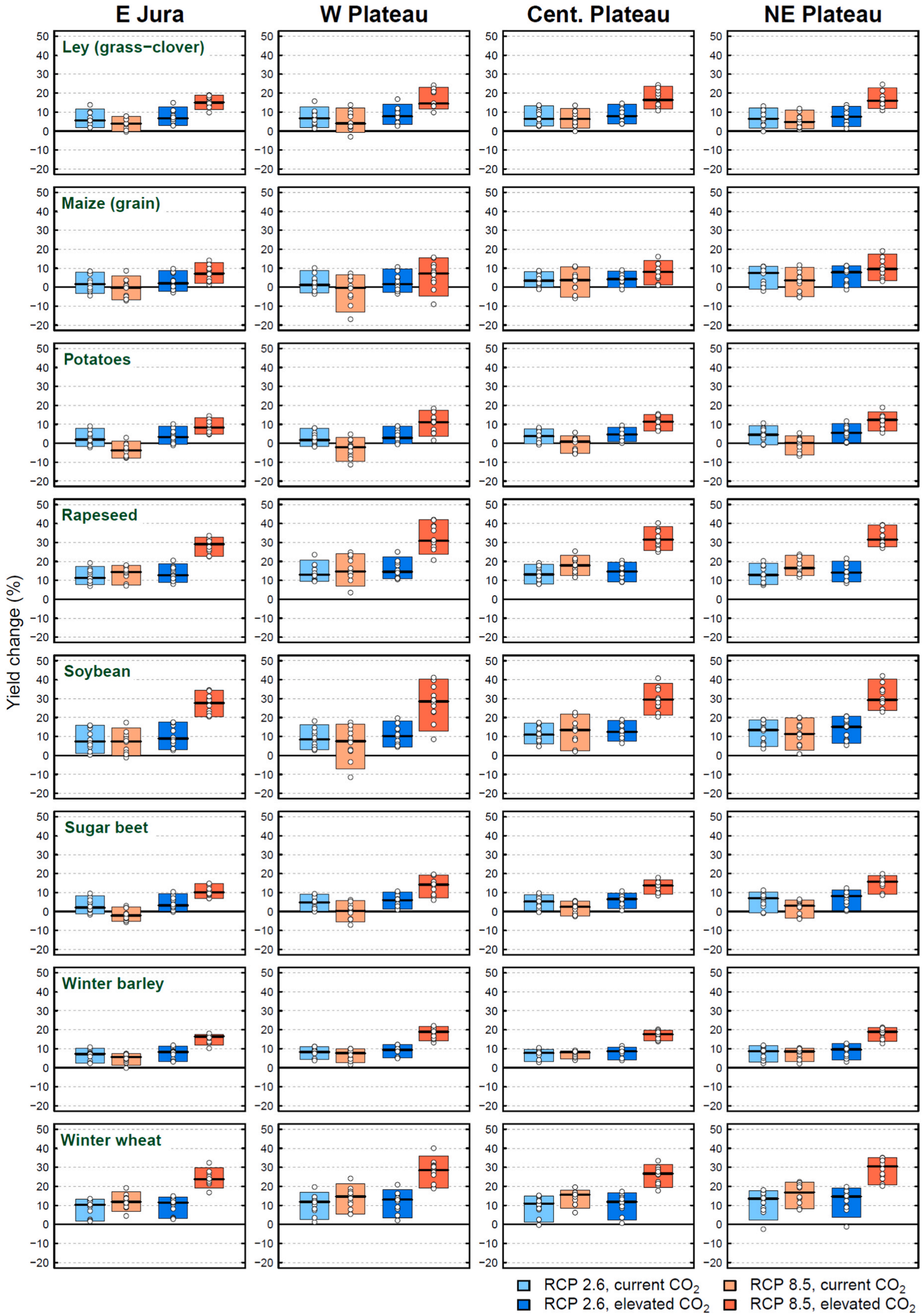

Fig. 3. Relative change in crop yield (2045–2074 *versus* 1981–2010) in different cropland regions in Switzerland for scenarios with stringent mitigation (RCP 2.6) and without mitigation (RCP 8.5), and with and without elevation of atmospheric CO_2 level. Individual simulations of the CH2018 model ensemble are represented by small open circles. The vertical extent of the colored bars indicates the 90 % quantile range of the uncertainty in the multi-model median value represented by horizontal bold line.

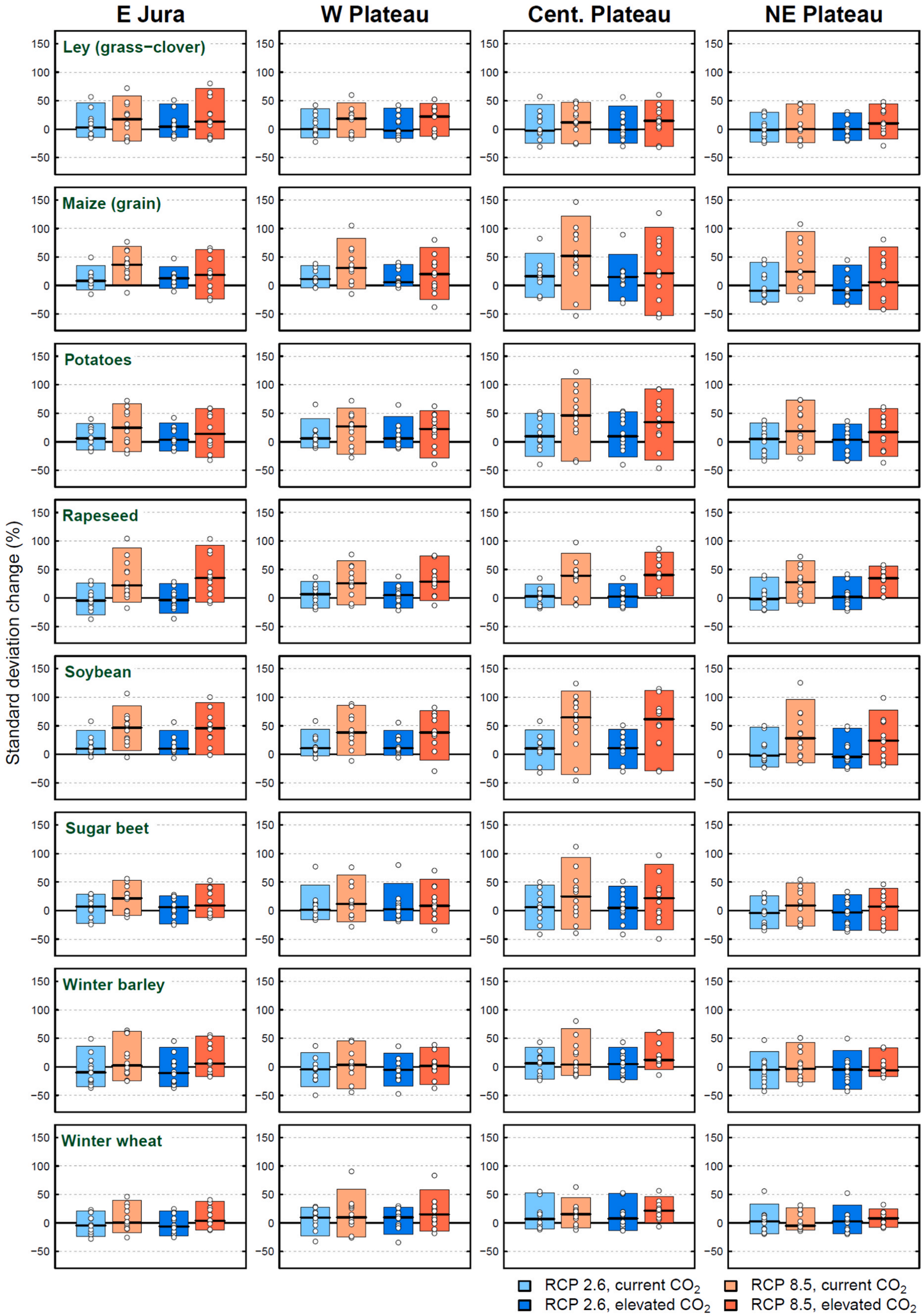

Fig. 4. Changes in the standard deviation (SD) of crop yields (2045–2074 *versus* 1981–2010) in different cropland regions in Switzerland for scenarios with stringent mitigation (RCP 2.6) and without mitigation (RCP 8.5), and with and without elevation of atmospheric CO_2 level. Individual simulations of the CH2018 model ensemble are represented by small open circles. The vertical extent of the colored bars indicates the 90 % quantile range of the uncertainty in the multi-model median value represented by horizontal bold line.

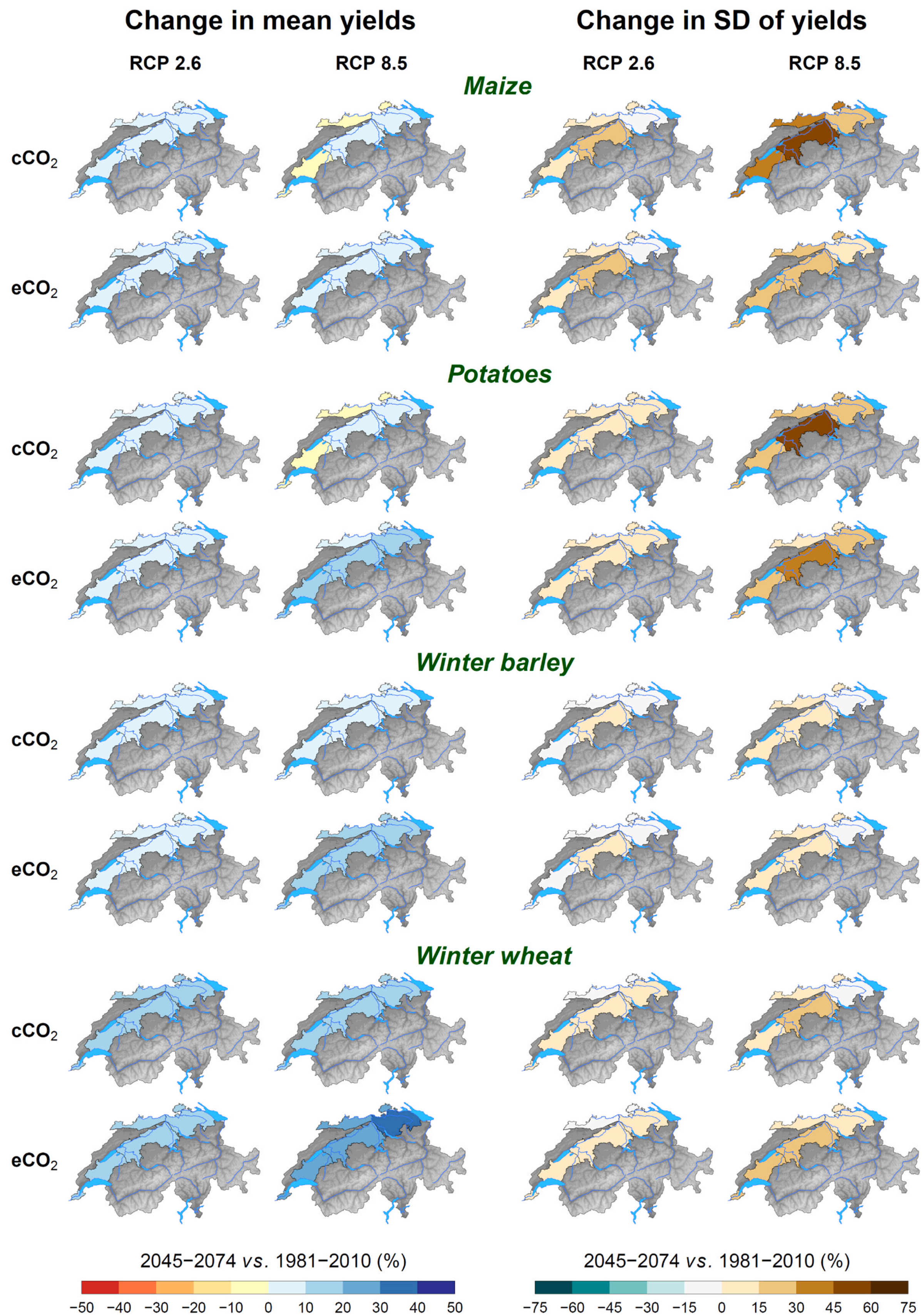

Fig. 5. Relative change in mean crop yields and standard deviation (SD) in different cropland regions in Switzerland for scenarios with stringent mitigation (RCP 2.6) and without mitigation (RCP 8.5), and with and without elevation of atmospheric CO_2 level (eCO_2 and cCO_2, respectively).

difference between projections of individual model chains for the same scenario and region (*cf.* length of the red bars in Fig. 3). For summer crops in Western and Central Plateau, there is normally a clear greater discrepancy between different climate models for RCP 8.5 compared to the scenario with RCP 2.6 (Fig. 3). The wider range of projections obtained for summer crops should be taken into account for a more robust interpretation of the RCP 8.5 scenario projections. For example, it can be observed that there is only a slight increase or slight decrease in the median value (median across the model chains) of the average yield levels in the projections obtained assuming current CO_2 levels (*cf.* light red bars in Fig. 3). However, for summer crops, a significant fraction of the individual model chains (48 % for maize, 46 % for sugar beet, 6 % for soybean, and 65 % for potatoes) indicate yield losses of up to −17 % for maize, −7 % for sugar beet, −12 % for soybean, and −11 % for potatoes (Fig. 3).

In relation to projection of changes in SD of crop yields, it is seen that for the RCP 2.6, the median values are generally close to zero, except for maize with median increase of 15 % in Central Plateau when the elevation in CO_2 is accounted for (Figs. 4, 5 and S3). In contrast, the median values for the scenario of RCP 8.5 show a likely substantial increase in the SD of yields especially for summer crops (Fig. 4). This is clearly shown in examples of maps for maize and potatoes *vs.* winter barley and winter wheat (Fig. 5). The Central Plateau is the region with the largest increase in the median projection of the SD of summer crop yields, amounting to 52 % for maize, 46 % for potatoes, 65 % for soybean, and 25 % for sugar beet, if the increase in CO_2 is not taken into account (Figs. 4, 5 and S3). This largest projected decrease in stability of summer crop yields in the Central Plateau assuming CO_2 fixed at present levels (no improvements of the water use efficiency) reflects the largest sensitivity of crop yield variability with respect to interannual precipitation variability under decreasing average precipitation amounts, *i.e.* more situations in which crop yield are limited by precipitation deficit (Fig. 2). Overall, it can be seen that elevation in CO_2 levels tends to alleviate the yield variability of summer crops, resulting in projected increases of 22 % for maize, 34 % for potatoes, 62 % for soybean, and 22 % for sugar beet in the Central Plateau (Figs. 4, 5 and S3). Although the dispersion of projections based on individual climate model chains under RCP 8.5 also presents discrepancy for summer crops, most individual chains consistently indicate an increase in SD of yields (*cf.* red bars in Fig. 4). When model chains are considered individually for the scenario without CO_2 elevation, the changes in SD for summer crops in the Central Plateau reach 146 % for maize, 123 % for potatoes, 125 % for soybean and 112 % for sugar beet (*cf.* dots in the red bars in Fig. 4).

With respect to winter crops, we noticed a trend toward improved yield stability in the future. Nevertheless, an important exception is rapeseed. Despite being a typical winter crop dependent on vernalization, rapeseed has a longer growing season than wheat and barley, and is usually harvested in mid-summer. As a result, it shows a projected increase in yield SD similar to that of summer crops under RCP 8.5 (Figs. 4 and S3). Therefore, rapeseed and soybean are the only crops departing from the overall tendency of the corresponding crop type, *i.e.* lower increase in SD for winter crops and lower increase in average yields for summer crops under the RCP 8.5 (Figs. 3–5 and S3).

4. Discussion

Understanding the response of different crops to future climate is the first step towards determining vulnerabilities and, consequently, the future risks associated with cropping systems. Our study contributes to filling a gap in knowledge about the response of various summer and winter crops to climate change in terms of yield stability based on a robust ensemble of climate models for Switzerland from the CH2018 framework. Our results of yield stability response to climate change, which was measured by the shift in SD of yields, emphasize the overall contrast between typical summer crops, *i.e.* growing throughout the summer (maize, potatoes and sugar beet), and cereal winter crops, which do not normally prolong their growth until the late summer (wheat and barley) (Figs. 4 and 5). Typical summer crops, including maize, potatoes and sugar beet, are the most likely to be negatively affected by climate change. A first critical example is maize, which is a crop that likely benefits the least from warming (Figs. 3 and 5), and the one with one of the largest risks of higher instability in yields (Figs. 4 and 5). Even the other summer crops (potatoes, soybean and sugar beet), which are C3 and therefore can benefit from elevation in CO_2 levels (Fig. S1), are likely to suffer significant reduction in yield stability (Figs. 4, 5 and S3). It is worth noting that soybean, despite having a low share of Swiss croplands, with less than 1 % of the area (FAOSTAT, 2025), is a legume crop that has great potential to increase the cultivated areas (Keller et al., 2024) and presented a clear projection of increase in the yields (Figs. 3 and S3). Due to the ability for biological N_2 fixation, reducing the use of nitrogen fertilizers, and the high protein and oil content in the grains, legume crops like soybean are considered strategic for the future, meeting the demand for a more sustainable diet (Keller et al., 2024). However, our results show that soybean can be a good option only if the increasing risk of yield instability is properly managed. Development of early maturing genotypes of this crop, as well of the other summer crops, avoiding drier conditions of late summer (Fig. 2), can be an adaptation option to be adopted in future (Holzkämper, 2020).

The importance of precipitation and temperature in summer period for the yield variability in the present study is shown by correlation values considering an example of extreme climate change scenario based on the climate model SMHI-RCA_MPIESM_EUR44 for the RCP 8.5 (Fig. S5). In this example, the strongest correlations with yields of summer crops were obtained for precipitation, with r values ranging from 0.78 to 0.81 ($P < 0.001$, Fig. S5), and for maximum temperature, with r values ranging from −0.81 to −0.89 ($P < 0.001$, Fig. S5). These results are in line with results of a global study including maize, rice, wheat and soybean indicating that climate variability causes more than 60 % of the yield variability in the major agricultural regions in the world (Ray et al., 2015). They are also consistent with a study conducted for Sweden, which reported that temperature and precipitation accounted for 75–85 % of the variability in cereal yields in the period of 1965–2020 (Tootoonchi et al., 2025).

The substantial decrease in yield stability of summer crops, as indicated in the present study (Figs. 4, 5, and S3), is a very critical economic aspect for adapting cropping systems to climate change. It directly affects the reliability by a farmer for definition of crop rotations (Brown and Kshirsagar, 2015; Tadesse et al., 2014). Yield stability is also critical for defining the insurability of crops. Our results shows that crops that grow during the summer should be the target of drought-related insurance strategies, which has proven to be of paramount importance as an adaptation solution to cope with the threat of yield losses due to climate change (Mao et al., 2025; Wang et al., 2022). The increased risk of shortage of products from summer crops can increase the dependency on imports, further reducing critically low food self-sufficiency of Switzerland in drier years, leading to more vulnerability to price shocks. The market for agricultural products is, by its nature, substantially inelastic (Barr et al., 2011; Orm, 2023; Rao, 1989), *i.e.* the impact of change in the production on the prices of the product is usually largely disproportionate. For example, a global study for maize showed that, from the 2010–2011 growing season, every 1 % reduction in maize production meant approximately a 5 % increase in the prices (Adjemian and Smith, 2012).

Regarding the regional variation in crop responses, it should be noted that for typical summer crops (maize, potatoes and sugar beet), there is trend of reduction in average yields in historically drier regions under the RCP 8.5 and with no CO_2 elevation (*cf.* Western Plateau and Eastern Jura in Fig. 2 and yellowish grades in the second column of maps in Figs. 5 and S3). In these two regions, maize is the crop with the highest risk of average yield loss in the mid-century under the RCP 8.5 (Fig. 3). On the other hand, the Central Plateau region is likely the region that will be most impacted in terms of decrease in yield stability for summer crops (Figs. 4, 5 and S3). In the reference period (1981–2010), the Central Plateau is the region with the highest precipitation levels throughout the year and, therefore, with the least water limitation for crop growth (Fig. 2). This is quite consistent with the lower yield variability for most crops in the Central Plateau in the reference period (Table 3), even with higher SD values for precipitation in comparison to drier regions (Fig. S4). Our results suggest that yield variability can critically increase in regions that have historically been less susceptible to drought-induced losses due to reduction of the dampening effect. The increase of temperature, reaching an upward trend of more than 2.5°C in mean temperatures in August (Fig. 2), will likely aggravate this reduction in the dampening effect due to increase in vapor pressure deficit, *i.e.* increasing evaporative demand of atmosphere (Poorter et al., 2012), resulting in higher evapotranspiration rates and, consequently, the decline in water use efficiency.

Under non-limiting water conditions, the positive response of C3 crops to elevated CO_2 levels is well documented (Durand et al., 2018; Elliott et al., 2014; Qian et al., 2019). However, there is great variability in responses for different crops and for different regions when crops are under water stress (Gray et al., 2016; Kimball, 2016; Manderscheid et al., 2014). This is consistent with our results showing that that the increase in CO_2 levels tends to reduce yield variability, but the intensity of this effect varied with the crop type (Figs. 4, 5 and S3). As maize barely profits directly from NPP stimulation, as shown in Fig. S1 (Supplementary Material), the higher reduction in yield variability for maize than for other crops suggests that the benefits of higher CO_2 concentrations are mostly associated with improved water use efficiency through reduced transpiration rates. This result is quite consistent with studies showing that positive impacts of elevation of CO_2 levels on yields of maize and other C4 crops (*e.g.*, millet and sorghum) occurs particularly under drought conditions (Ainsworth and Long, 2021; Manderscheid et al., 2014; Rezaei et al., 2023).

Regarding winter crops, the warming of the spring period (Fig. 2), providing thermal units for growth and an earlier start to the growing season (Calanca et al., 2023), coupled with greater water availability during this phase (Fig. 2) explains part of the tendency of having positive impact on yields, particularly under the RCP 8.5 (>20 %), based on the whole ensemble of climate models (Figs. 3, 5 and S3). Our results are well in line with a study for Sweden for the period of 1965–2020 showing that the cereal yields can benefit from warming when it is associated to increased precipitation levels (Tootoonchi et al., 2025). On the other hand, the levels of yield increase for winter crops in the present study are above model projections made for European conditions in other studies. For winter wheat, for example, a broad study for Europe indicated a yield increase of about 4 % (Webber et al., 2018). In contrast, considering other regions of the world that are suitable for winter crops, there are two studies for Canada projecting future yield increases of around 70 % for wheat (Smith et al., 2013; Wang et al., 2012). In another large-scale study for that country, based on three process-based crop models and downscaled data from 20 climate models, Qian et al. (2019) found increases up to 20 % for wheat and 10 % for rapeseed.

To avoid an overly optimistic interpretation of the projected increases in winter crop yields in the present study (Figs. 3 and 5), the absence of nutritional stress cannot be disregarded as a factor affecting the response of the crops to climate and CO_2 elevation (Rosenzweig et al., 2014). Nutrient limitation might probably counteract yield increases induced by warming and CO_2 fertilization. This is in agreement with the results of a modeling study for EU countries with a 2050-time horizon, which demonstrates that N limitation exacerbates the negative impact of climate change on winter crop yields (Webber et al., 2015). For example, in that study, the relative yield changes of winter wheat, aggregated at European level, ranged from +7 % to +14 % without N limitation and decreased to a range of −4 to +4 % when N limitation was considered. It should be noted that in the mid-century there may be a reduction in fertilization in European cropping systems in order to increase sustainability (*e.g.*, European Commission, 2024). Switzerland also has strategies to increase sustainability that are in line with those of the European Commission (*cf.* "Agriculture and Food Climate Strategy 2050", FOAG, 2025). Therefore, the role of nutrient level should be further explored in future studies addressing climate change impacts on Swiss cropping systems, including the role of biological N_2 fixation in legume crops. For instance, there are long-term field studies indicating that diversifying crop rotations with legumes is an effective strategy for preserving average yields (Knapp et al., 2023) and for improving yield stability (Gaudin et al., 2015).

Although CO_2 elevation tends to increase crop yields in our projections, particularly for winter crops under the RCP 8.5 (Figs. 3 and 5), which is coherent with the literature (Ainsworth and Long, 2005, 2021; Kimball, 2016; Kimball et al., 1995), the uncertainty associated with the CO_2 effect in some crop types is not negligible and should be taken into account for a careful interpretation (*e.g.*, Gray et al., 2016; Schauberger et al., 2017; Webber et al., 2018). For example, in the meta-analysis of FACE field observations used as a reference for the present study (Ainsworth and Long, 2005), the factor of 1.144 considered for the effect of CO_2 elevation on wheat productivity (Fig. S1), is associated with a 95 % confidence interval ranging from 0.984, *i.e.* slight suppression effect of CO_2 elevation on wheat yields, to 1.331, *i.e.* a significant stimulation of growth. Furthermore, even if the CO_2 elevation increases yields, there is also a well-documented critical side effect, which is the reduction in the quality of harvestable crop products due to an increase in C-to-nutrient ratio (Ebi and Loladze, 2019; Loladze, 2002). For instance, the protein content of harvested products generally decreases under elevated CO_2 levels, representing a decrease in the nutritional value of food (Beach et al., 2019; Högy et al., 2009; Myers et al., 2014). Harvested products may also become depleted in essential trace elements for human nutrition, such as iron and zinc (Dong et al., 2018; Högy et al., 2009) which can lead to a serious health problem known as "hidden hunger" (Loladze, 2002; Schmitt, 2024). This likely reduction in quality needs to be considered in conjunction to the projected increases in crop yields (Figs. 3 and 5).

Regarding the results of the climate models used in this study, we believe that if we had used results from CMIP6 instead of CMIP5, which was the basis for the downscaling procedure in the CH2018 framework, we would likely have obtained slightly different projections, although with the same trends. In CMIP6, the highest emission scenario (SSP5–8.5) has slightly higher atmospheric CO_2 concentrations and slightly stronger climate change signals than under RCP 8.5 in CMIP5 (Hausfather, 2019; Jägermeyr et al., 2021; Meehl et al., 2020). Therefore, it is likely that projections based on CMIP6 would result in some exacerbation of the impact of climate change on crops, including even lower yield stability for summer crops and a greater tendency for average yield of winter crops to increase (Hausfather, 2019). Such trends would be in keeping with a previous global study showing more pessimistic projections for the end of the century for maize and more optimistic projections for wheat when modeling is based on CMIP6 instead of CMIP5 (Jägermeyr et al., 2021).

Other factors that can alter crop yield and yield stability due to the changing climatic conditions should be explored in more detail in further research. One critical point is the increased occurrence of heat stress (Bernacchi et al., 2025; Briggs and Anderson, 2024; Janni et al., 2024). We consider this factor should be explored in the future, especially in terms of finer time granularities. Modeling based on daily time steps, typically used in crop modeling studies, may not be sufficient to capture stresses related to temperature peaks at critical phenological stages of crops, such as flowering (Djalovic et al., 2024; Poudel et al., 2024). Other factors, such as flooding and water-stagnation in soil surface are also well recognized as potential problems for crop growth under future climatic conditions (Olesen et al., 2011) and should be further addressed in future studies. On the other hand, we do not overlook the fact that potential technological improvements that were not incorporated in our projections, such as those based on plant breeding efforts (*e.g.*, development of drought-tolerant cultivars), can affect the response of crops to climate change (Stella et al., 2023) and should be further explored by modeling the impact of mitigation and adaptation measures in future cropping systems.

Overall, even considering the above-mentioned limitations of this study, we believe that our results are useful in guiding future strategies aimed at farmers and policymakers to cope with negative impacts of climate change on crops. We consider that two key advantages of our study are the use outputs of a robust set of climate models (12 for each RCP) and a fairly comprehensive number of crops (8 in total) representative of Switzerland and Western Europe in general in our simulations. Furthermore, combining estimates of the impact on yield with measures of year-to-year variability, expressed as SD, also provides projections of great practical interest, for example for the insurance industry and the food market. For instance, the risk weighing for development of tailored insurance products and the use of selected tolerant crop types in crop rotations to buffer some of the deleterious impacts of climate change, especially in terms of yield instability, can help to maintaining food supply with manageable price volatility under future conditions.

5. Conclusions

Our projections suggest that the average yields of most crops tend to increase in the mid-century as a result of warming and elevated CO_2 levels, especially for winter crops and soybean under RCP 8.5, although associated with a considerable divergence within the ensemble of climate models. Maize is the crop most vulnerable to average yield losses, particularly in typically drier regions, *viz.* Western Plateau and Eastern Jura. Under RCP 8.5, a substantial decline in yield stability is consistently projected for all summer crops, generally higher than for winter crops. The Central Plateau is likely the region where summer crops will suffer the greatest decrease in yield stability, with SD values increasing by more than 50 % for maize, 40 % for potatoes, 60 % for soybean and 25 % for sugar beet. Elevated CO_2 levels is likely to overall alleviate this negative impact, especially for maize for which the projected increase in SD in Central Plateau is reduced to *ca.* 20 %. Our results suggest that, for the summer crops in Central Plateau, the large projected decrease in yield stability is due to the weakening of the dampening effect of the precipitation amount in this region, which tends to decrease in summer in mid-century, which is compounded by increased evapotranspirative demand due to higher temperature. In contrast, for cereal winter crops such as wheat and barley, there are likely to be milder reductions in yield stability, regardless of the scenarios and the CO_2 levels considered in the present study. The contrast between typical summer crops and cereal winter crops indicated in this study should be taken into account when determining the economic viability of cropping systems, developing the best insurance strategies, and ensuring food security under future climate conditions.

CRediT authorship contribution statement

Márcio dos Reis Martins: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Pierluigi Calanca:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors did not use any generative AI or AI-assisted technologies.

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.

Acknowledgements

This study was supported by the Swiss National Centre for Climate Services (NCCS) in the framework of the NCCS Impacts program (Ecosystem Services).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2025.127855.

Data Availability

The data of modeled crop yields based on the outputs of different climate models from the CH2018 framework are published in the Zenodo repository at doi:10.5281/zenodo.17107638.

References

Adjemian, M.K., Smith, A., 2012. Using USDA forecasts to estimate the price flexibility of demand for agricultural commodities. Am. J. Agr. Econ. 94, 978–995. https://doi.org/10.1093/ajae/aas032.
Adler, P.R., Spatari, S., D'Ottone, F., Vazquez, D., Peterson, L., Del Grosso, S.J., Baethgen, W.E., Parton, W.J., 2018. Legacy effects of individual crops affect N_2O emissions accounting within crop rotations. GCB Bioenergy 10, 123–136. https://doi.org/10.1111/gcbb.12462.
Ainsworth, E.A., Long, S.P., 2005. What have we learned from 15 years of free-air CO_2 enrichment (FACE)? a meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2. N. Phytol. 165, 351–372. https://doi.org/10.1111/j.1469-8137.2004.01224.x.
Ainsworth, E.A., Long, S.P., 2021. 30 years of free-air carbon dioxide enrichment (FACE): what have we learned about future crop productivity and its potential for adaptation? Glob. Change Biol. 27, 27–49. https://doi.org/10.1111/gcb.15375.
Barr, K.J., Babcock, B.A., Carriquiry, M.A., Nassar, A.M., Harfuch, L., 2011. Agricultural land elasticities in the United States and Brazil. Appl. Econ. Perspect. Policy 33, 449–462. https://doi.org/10.1093/aepp/ppr011.
Beach, R.H., Sulser, T.B., Crimmins, A., Cenacchi, N., Cole, J., Fukagawa, N.K., Mason-D'Croz, D., Myers, S., Sarofim, M.C., Smith, M., Ziska, L.H., 2019. Combining the effects of increased atmospheric carbon dioxide on protein, iron, and zinc availability and projected climate change on global diets: a modelling study. Lancet Planet. Health 3, e307–e317. https://doi.org/10.1016/S2542-5196(19)30094-4.
Berkhout, F., Dow, K., 2023. Limits to adaptation: building an integrated research agenda. WIREs Clim. Change 14, e817. https://doi.org/10.1002/wcc.817.
Bernacchi, C.J., Long, S.P., Ort, D.R., 2025. Safeguarding crop photosynthesis in a rapidly warming world. Science 388, 1153–1160. https://doi.org/10.1126/science.adv5413.
Briggs, S.D., Anderson, J.T., 2024. The effect of global change on the expression and evolution of floral traits. Ann. Bot. 135, 9–24. https://doi.org/10.1093/aob/mcae057.
Brown, M.E., Kshirsagar, V., 2015. Weather and international price shocks on food prices in the developing world. Glob. Environ. Change 35, 31–40. https://doi.org/10.1016/j.gloenvcha.2015.08.003.
Bürgi, M., 2016. Agricultural history of Switzerland. Historical approach – Land Use History and Historical Ecology. ETH, Zurich, Switzerland.
Calanca, P., Holzkämper, A., Isotta, F.A., 2023. Klimawandel führt zu längerer vegetationszeit und begünstigt höher gelegene Anbauflächen (Climate change leads to longer growing seasons and favors higher-altitude cultivation areas). Agrar. Schweiz 14, 150–158. https://doi.org/10.34776/afs14-150.
Cammarano, D., Tian, D., 2018. The effects of projected climate and climate extremes on a winter and summer crop in the southeast USA. Agric. For. Meteor. 248, 109–118. https://doi.org/10.1016/j.agrformet.2017.09.007.
CH2018, 2018. CH2018 – Climate scenarios for Switzerland, Technical Report. National Centre for Climate Services, Zurich, 271 pp.
CH2018 Project Team, 2018. CH2018 – Climate scenarios for Switzerland, National Centre for Climate Services, NCCS [dataset].
Chatzopoulos, T., Pérez Domínguez, I., Zampieri, M., Toreti, A., 2020. Climate extremes and agricultural commodity markets: a global economic analysis of regionally simulated events. Weather Clim. Extrem 27, 100193. https://doi.org/10.1016/j.wace.2019.100193.
Chou, S., Lyra, A., Mourão, C., Dereczynski, C., Pilotto, I., Gomes, J., Bustamante, J., Tavares, P., Silva, A., Rodrigues, D., Campos, D., Chagas, D., Sueiro, G., Siqueira, G., Marengo, J., 2014. Assessment of climate change over South America under RCP 4.5 and 8.5 downscaling scenarios. Am. J. Clim. Change 3, 512–527. https://doi.org/10.4236/ajcc.2014.35043.
Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, C., Carrara, A., Chevallier, F., De Noblet, N., Friend, A.D.,

Friedlingstein, P., Grünwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J.M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J.F., Sanz, M.J., Schulze, E.D., Vesala, T., Valentini, R., 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437, 529–533. https://doi.org/10.1038/nature03972.

Cure, J.D., Acock, B., 1986. Crop responses to carbon dioxide doubling: a literature survey. Agr. For. Meteor. 38, 127–145. https://doi.org/10.1016/0168-1923(86)90054-7.

Darwin, R., Kennedy, D., 2000. Economic effects of CO_2 fertilization of crops: transforming changes in yield into changes in supply. Environ. Model. Assess. 5, 157–168. https://doi.org/10.1023/A:1019013712133.

Deutsche Welle, 2018. Calls for farm support intensify as Europe struggles with heat wave, drought. https://dw.com/en/calls-for-farm-support-intensify-as-europe-struggles-with-heat-wave-drought/a-44902321. (accessed 20 March 2025).

Djalovic, I., Kundu, S., Bahuguna, R.N., Pareek, A., Raza, A., Singla-Pareek, S.L., Prasad, P.V.V., Varshney, R.K., 2024. Maize and heat stress: physiological, genetic, and molecular insights. Plant Genome 17, e20378. https://doi.org/10.1002/tpg2.20378.

Dong, J., Gruda, N., Lam, S.K., Li, X., Duan, Z., 2018. Effects of elevated CO_2 on nutritional quality of vegetables: a review. Front. Plant Sci. 9, 924. https://doi.org/10.3389/fpls.2018.00924.

Dow, K., Berkhout, F., Preston, B.L., 2013. Limits to adaptation to climate change: a risk approach. Curr. Opin. Environ. Sustain 5, 384–391. https://doi.org/10.1016/j.cosust.2013.07.005.

Durand, J.-L., Delusca, K., Boote, K., Lizaso, J., Manderscheid, R., Weigel, H.J., Ruane, A.C., Rosenzweig, C., Jones, J., Ahuja, L., Anapalli, S., Basso, B., Baron, C., Bertuzzi, P., Biernath, C., Deryng, D., Ewert, F., Gaiser, T., Gayler, S., Heinlein, F., Kersebaum, K.C., Kim, S.-H., Müller, C., Nendel, C., Olioso, A., Priesack, E., Villegas, J.R., Ripoche, D., Rötter, R.P., Seidel, S.I., Srivastava, A., Tao, F., Timlin, D., Twine, T., Wang, E., Webber, H., Zhao, Z., 2018. How accurately do maize crop models simulate the interactions of atmospheric CO_2 concentration levels with limited water supply on water use and yield? Eur. J. Agron. 100, 67–75. https://doi.org/10.1016/j.eja.2017.01.002.

Ebi, K.L., Loladze, I., 2019. Elevated atmospheric CO_2 concentrations and climate change will affect our food's quality and quantity. Lancet Planet. Health 3, e283–e284. https://doi.org/10.1016/S2542-5196(19)30108-1.

Elliott, J., Deryng, D., Müller, C., Frieler, K., Konzmann, M., Gerten, D., Glotter, M., Flörke, M., Wada, Y., Best, N., Eisner, S., Fekete, B.M., Folberth, C., Foster, I., Gosling, S.N., Haddeland, I., Khabarov, N., Ludwig, F., Masaki, Y., Olin, S., Rosenzweig, C., Ruane, A.C., Satoh, Y., Schmid, E., Stacke, T., Tang, Q., Wisser, D., 2014. Constraints and potentials of future irrigation water availability on agricultural production under climate change. Proc. Natl. Acad. Sci. 111, 3239–3244. https://doi.org/10.1073/pnas.1222474110.

EURO-CORDEX, 2024. EURO-CORDEX - Coordinated Downscaling Experiment - European Domain. https://www.euro-cordex.net. (accessed 06 November 2024).

European Commission, 2024. Farm to Fork Strategy. https://food.ec.europa.eu/horizontal-topics/farm-fork-strategy_en. (accessed 07 March 2025).

FAOSTAT, 2025. Crops and livestock products. Food and Agricultural Organization of the United Nations - Statistics Division. http://www.fao.org/faostat. (accessed 24 January 2025).

Feigenwinter, I., Kotlarski, S., Casanueva, A., Fischer, A.M., Schwierz, C., Liniger, M.A., 2018. Exploring quantile mapping as a tool to produce user-tailored climate scenarios for Switzerland, Technical Report No. 270. MeteoSwiss, Zurich, Switzerland, 44 pp.

FOAG, 2024a. Agrarbericht 2024 - Selbstversorgungsgrad (Agricultural Report 2024 – Degree of self-sufficiency). https://www.agrarbericht.ch/de/markt/marktentwicklungen/selbstversorgungsgrad (accessed 26 May 2025).

FOAG, 2024b. Landwirtschaftliche Kulturflächen: Identifikator 153 – Bezugsjahr 2024 (Agricultural land: Identifier 153 – Reference year 2024). Federal Office for Agriculture (FOAG). https://www.blw.admin.ch/blw/de/home/politik/datenmanagement/geografisches-informationssystem-gis/landwirtschaftliche-kulturflaechen.html (accessed 10 December 2024).

FOAG, 2025. Agriculture and Food Climate Strategy 2050. https://www.blw.admin.ch/en/agriculture-and-food-climate-strategy-2050. (accessed 30 May 2025).

Gaudin, A.C.M., Tolhurst, T.N., Ker, A.P., Janovicek, K., Tortora, C., Martin, R.C., Deen, W., 2015. Increasing crop diversity mitigates weather variations and improves yield stability. PLOS One 10, e0113261. https://doi.org/10.1371/journal.pone.0113261.

Gbegbelegbe, S., Chung, U., Shiferaw, B., Msangi, S., Tesfaye, K., 2014. Quantifying the impact of weather extremes on global food security: a spatial bio-economic approach. Weather Clim. Extrem 4, 96–108. https://doi.org/10.1016/j.wace.2014.05.005.

Ghosh, A., Kumar, A., Biswas, G., 2024. Chapter 1 - exponential population growth and global food security: challenges and alternatives. In: Kumar, P., Srivastav, A.L., Chaudhary, V., van Hullebusch, E.D., Busquets, R. (Eds.), Bioremediation of Emerging Contaminants from Soils. Elsevier, pp. 1–20. https://doi.org/10.1016/B978-0-443-13993-2.00001-3.

Gifford, R.M., 1979. Carbon dioxide and plant growth under water and light stress: implications for balancing the global carbon budget. Search 10, 316–318.

Gifford, R.M., 1980. Carbon storage by the biosphere. In: Pearman, G.I. (Ed.), Carbon Dioxide and Climate: Australian Research. Australian Academy of Science, Canberra, Australia, pp. 167–181.

Giorgi, F., Jones, C., Asrar, G.R., 2009. Addressing climate information needs at the regional level: the CORDEX framework. WMO Bull. 58, 175.

Goudriaan, J., 1992. Biosphere structure, carbon sequestering potential and the atmospheric ^{14}C record. J. Exp. Bot. 43, 1111–1119. https://doi.org/10.1093/jxb/43.8.1111.

Goudriaan, J., Vanlaar, H.H., Van Keulen, H., Louwerse, W., 1985. Photosynthesis, CO_2 and plant production, in: {C}Day, W., Atkin, R.K. (Eds{C}.), Wheat growth and modelling. NATO ASI Series, Series A: Life Sciences, Vol. 86. Plenum Press, New York, USA, pp. 107–122.

Grant, B.B., Smith, W.N., Campbell, C.A., Desjardins, R.L., Lemke, R.L., Kröbel, R., McConkey, B.G., Smith, E.G., Lafond, G.P., 2016. Comparison of DayCent and DNDC models: case studies using data from long-term experiments on the Canadian prairies. In: Del Grosso, S.J., Ahuja, L.R., Parton, W.J. (Eds.), Synthesis and modeling of greenhouse gas emissions and carbon storage in agricultural and forest systems to guide mitigation and adaptation. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, USA, pp. 21–57.

Gray, S.B., Dermody, O., Klein, S.P., Locke, A.M., McGrath, J.M., Paul, R.E., Rosenthal, D.M., Ruiz-Vera, U.M., Siebers, M.H., Strellner, R., Ainsworth, E.A., Bernacchi, C.J., Long, S.P., Ort, D.R., Leakey, A.D.B., 2016. Intensifying drought eliminates the expected benefits of elevated carbon dioxide for soybean. Nat. Plants 2, 16132. https://doi.org/10.1038/nplants.2016.132.

Hartman, M.D., Parton, W.J., Grosso, S.J.D., M. Easter, Hendryx, J., Hilinski, T., Kelly, R., Keough, C.A., Killian, K., Lutz, S., Marx, E., McKewon, R., Ogle, S., Ojima, D.S., Paustian, K., Swan, A., Williams, S., 2019. DayCent Ecosystem Model. The Daily Century Ecosystem, Soil organic Matter, Nutrient Cycling, Nitrogen Trace Gas, and Methane Model. User Manual, Scientific Basis, and Technical Documentation. Colorado State University, Fort Collins, USA.

Hausfather, Z., 2019. CMIP6 Gener. Clim. Models Explain. Carbon Brief. https://www.carbonbrief.org/cmip6-the-next-generation-of-climate-models-explained. (accessed 07 August 2025).

Headey, D.D., Martin, W.J., 2016. The impact of food prices on poverty and food security. Annu. Rev. Resour. Econ. 8, 329–351. https://doi.org/10.1146/annurev-resource-100815-095303.

Hocking, P., Meyer, C., 1991. Effects of CO_2 enrichment and nitrogen stress on growth, and partitioning of dry matter and nitrogen in wheat and maize. Funct. Plant Biol. 18, 339–356. https://doi.org/10.1071/PP9910339.

Högy, P., Wieser, H., Köhler, P., Schwadorf, K., Breuer, J., Franzaring, J., Muntifering, R., Fangmeier, A., 2009. Effects of elevated CO_2 on grain yield and quality of wheat: results from a 3-year free-air CO_2 enrichment experiment. Plant Biol. 11, 60–69. https://doi.org/10.1111/j.1438-8677.2009.00230.x.

Holzkämper, A., 2020. Varietal adaptations matter for agricultural water use–a simulation study on grain maize in Western Switzerland. Agric. Water Manag 237, 106202. https://doi.org/10.1016/j.agwat.2020.106202.

Iizumi, T., Ramankutty, N., 2016. Changes in yield variability of major crops for 1981–2010 explained by climate change. Environ. Res. Lett. 11, 034003. https://doi.org/10.1088/1748-9326/11/3/034003.

Iqbal, J., Necpalova, M., Archontoulis, S.V., Anex, R.P., Bourguignon, M., Herzmann, D., Mitchell, D.C., Sawyer, J.E., Zhu, Q., Castellano, M.J., 2018. Extreme weather-year sequences have nonadditive effects on environmental nitrogen losses. Glob. Change Biol. 24, e303–e317. https://doi.org/10.1111/gcb.13866.

Jägermeyr, J., Müller, C., Ruane, A.C., Elliott, J., Balkovic, J., Castillo, O., Faye, B., Foster, I., Folberth, C., Franke, J.A., Fuchs, K., Guarin, J.R., Heinke, J., Hoogenboom, G., Iizumi, T., Jain, A.K., Kelly, D., Khabarov, N., Lange, S., Lin, T.-S., Liu, W., Mialyk, O., Minoli, S., Moyer, E.J., Okada, M., Phillips, M., Porter, C., Rabin, S.S., Scheer, C., Schneider, J.M., Schyns, J.F., Skalsky, R., Smerald, A., Stella, T., Stephens, H., Webber, H., Zabel, F., Rosenzweig, C., 2021. Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. Nat. Food 2, 873–885. https://doi.org/10.1038/s43016-021-00400-y.

Janni, M., Maestri, E., Gullì, M., Marmiroli, M., Marmiroli, N., 2024. Plant responses to climate change, how global warming May impact on food security: a critical review. Front. Plant Sci. 14, 1297569. https://doi.org/10.3389/fpls.2023.1297569.

Katul, G., Manzoni, S., Palmroth, S., Oren, R., 2009. A stomatal optimization theory to describe the effects of atmospheric CO_2 on leaf photosynthesis and transpiration. Ann. Bot. 105, 431–442. https://doi.org/10.1093/aob/mcp292.

Kaufmann, L., Mayer, A., Matej, S., Kalt, G., Lauk, C., Theurl, M.C., Erb, K.-H., 2022. Regional self-sufficiency: a multi-dimensional analysis relating agricultural production and consumption in the european union. Sustain. Prod. Consum 34, 12–25. https://doi.org/10.1016/j.spc.2022.08.014.

Keller, B., Oppliger, C., Chassot, M., Ammann, J., Hund, A., Walter, A., 2024. Swiss agriculture can become more sustainable and self-sufficient by shifting from forage to grain legume production. Commun. Earth Environ. 5, 40. https://doi.org/10.1038/s43247-023-01139-z.

Kimball, B.A., 2016. Crop responses to elevated CO_2 and interactions with H_2O, N, and temperature. Curr. Opin. Plant Biol. 31, 36–43. https://doi.org/10.1016/j.pbi.2016.03.006.

Kimball, B.A., Pinter Jr, P.J., Garcia, R.L., Lamorte, R.L., Wall, G.W., Hunsaker, D.J., Wechsung, G., Wechsung, F., Kartschall, T., 1995. Productivity and water use of wheat under free-air CO_2 enrichment. Glob. Change Biol. 1, 429–442. https://doi.org/10.1111/j.1365-2486.1995.tb00041.x.

Knapp, S., Gunst, L., Mäder, P., Ghiasi, S., Mayer, J., 2023. Organic cropping systems maintain yields but have lower yield levels and yield stability than conventional systems – results from the DOK trial in Switzerland. Field Crop. Res. 302, 109072. https://doi.org/10.1016/j.fcr.2023.109072.

Larcher, W., 2003. Physiological plant ecology, fourth ed. Springer, Berlin, Germany, 513 pp.

Lobell, D.B., Schlenker, W., Costa-Roberts, J., 2011. Climate trends and global crop production since 1980. Science 333, 616–620. https://doi.org/10.1126/science.1204531.

Loladze, I., 2002. Rising atmospheric CO_2 and human nutrition: toward globally imbalanced plant stoichiometry? Trends Ecol. Evol. 17, 457–461. https://doi.org/10.1016/S0169-5347(02)02587-9.
Mäder, P., Fliessbach, A., Dubois, D., Gunst, L., Fried, P., Niggli, U., 2002. Soil fertility and biodiversity in organic farming. Science 296, 1694–1697. https://doi.org/10.1126/science.1071148.
Manderscheid, R., Erbs, M., Weigel, H.-J., 2014. Interactive effects of free-air CO_2 enrichment and drought stress on maize growth. Eur. J. Agron. 52, 11–21. https://doi.org/10.1016/j.eja.2011.12.007.
Mao, H., Sun, Z., Chai, A., Fang, L., Shi, C., 2025. Extreme weather, agricultural insurance and farmer's climate adaptation technologies adoption in China. Ecol. Econ. 228, 108456. https://doi.org/10.1016/j.ecolecon.2024.108456.
Martins, M.R., Necpalova, M., Ammann, C., Buchmann, N., Calanca, P., Flechard, C.R., Hartman, M.D., Krauss, M., Le Roy, P., Mäder, P., Maier, R., Morvan, T., Nicolardot, B., Skinner, C., Six, J., Keel, S.G., 2022. Modeling N_2O emissions of complex cropland management in Western Europe using DayCent: performance and scope for improvement. Eur. J. Agron. 141, 126613. https://doi.org/10.1016/j.eja.2022.126613.
Mayer, J., Gunst, L., Mäder, P., Samson, M.-F., Carcea, M., Narducci, V., Thomsen, I.K., Dubois, D., 2015. Productivity, quality and sustainability of winter wheat under long-term conventional and organic management in Switzerland. Eur. J. Agron. 65, 27–39. https://doi.org/10.1016/j.eja.2015.01.002.
Meehl, G.A., Senior, C.A., Eyring, V., Flato, G., Lamarque, J.-F., Stouffer, R.J., Taylor, K.E., Schlund, M., 2020. Context for interpreting equilibrium climate sensitivity and transient climate response from the CMIP6 earth system models. Sci. Adv. 6, eaba1981. https://doi.org/10.1126/sciadv.aba1981.
Meinshausen, M., Smith, S.J., Calvin, K., Daniel, J.S., Kainuma, M.L.T., Lamarque, J.F., Matsumoto, K., Montzka, S.A., Raper, S.C.B., Riahi, K., Thomson, A., Velders, G.J.M., van Vuuren, D.P.P., 2011. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Clim. Change 109, 213. https://doi.org/10.1007/s10584-011-0156-z.
Mottaleb, K.A., Mohanty, S., Hoang, H.T.K., Rejesus, R.M., 2013. The effects of natural disasters on farm household income and expenditures: a study on rice farmers in Bangladesh. Agric. Syst. 121, 43–52. https://doi.org/10.1016/j.agsy.2013.06.003.
Myers, S.S., Zanobetti, A., Kloog, I., Huybers, P., Leakey, A.D.B., Bloom, A.J., Carlisle, E., Dietterich, L.H., Fitzgerald, G., Hasegawa, T., Holbrook, N.M., Nelson, R.L., Ottman, M.J., Raboy, V., Sakai, H., Sartor, K.A., Schwartz, J., Seneweera, S., Tausz, M., Usui, Y., 2014. Increasing CO_2 threatens human nutrition. Nature 510, 139–142. https://doi.org/10.1038/nature13179.
NCCS, 2025. The National Centre for Climate Services NCCS. https://www.nccs.admin.ch/nccs/en/home/the-nccs/about-the-nccs.html . (accessed 26 May 2025).
Necpalova, M., Lee, J., Skinner, C., Büchi, L., Wittwer, R., Gattinger, A., van der Heijden, M., Mäder, P., Charles, R., Berner, A., Mayer, J., Six, J., 2018. Potentials to mitigate greenhouse gas emissions from Swiss agriculture. Agric. Ecosyst. Environ. 265, 84–102. https://doi.org/10.1016/j.agee.2018.05.013.
Olesen, J.E., Trnka, M., Kersebaum, K.C., Skjelvåg, A.O., Seguin, B., Peltonen-Sainio, P., Rossi, F., Kozyra, J., Micale, F., 2011. Impacts and adaptation of european crop production systems to climate change. Eur. J. Agron. 34, 96–112. https://doi.org/10.1016/j.eja.2010.11.003.
Orm, M.P., 2023. MSc. thesis. Norwegian university of life sciences, Ås. EU wheat Prod. 's. Area Response Prices. Clim. Price risk. https://nmbu.brage.unit.no/nmbu-xmlui/handle/11250/3080252 (accessed 22 March 2025).
Ostberg, S., Schewe, J., Childers, K., Frieler, K., 2018. Changes in crop yields and their variability at different levels of global warming. Earth Syst. Dynam 9, 479–496. https://doi.org/10.5194/esd-9-479-2018.
Poorter, H., Fiorani, F., Stitt, M., Schurr, U., Finck, A., Gibon, Y., Usadel, B., Munns, R., Atkin, O.K., Tardieu, F., Pons, T.L., 2012. The art of growing plants for experimental purposes: a practical guide for the plant biologist. Funct. Plant Biol. 39, 821–838. https://doi.org/10.1071/FP12028.
Porter, J., Xie, L., Challinor, A.J., Howden, M., Iqbal, M.M., Lobell, D.B., Travasso, M.I., 2014. Food security and food production systems. In: Field, C.B., Barros, V.R., et al. (Eds.), Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and Sectoral Aspects. Cambridge University Press, Cambridge, UK, pp. 485–533 (accessed 10 March 2025). https://www.ipcc.ch/report/ar5/wg2.
Poudel, S., Vennam, R.R., Sankarapillai, L.V., Liu, J., Reddy, K.R., Wijewardane, N.K., Mukhtar, M.S., Bheemanahalli, R., 2024. Negative synergistic effects of drought and heat during flowering and seed setting in soybean. Environ. Exp. Bot. 222, 105769. https://doi.org/10.1016/j.envexpbot.2024.105769.
Qian, B., Zhang, X., Smith, W., Grant, B., Jing, Q., Cannon, A.J., Neilsen, D., McConkey, B., Li, G., Bonsal, B., Wan, H., Xue, L., Zhao, J., 2019. Climate change impacts on Canadian yields of spring wheat, canola and maize for global warming levels of 1.5 °C, 2.0 °C, 2.5 °C and 3.0 °C. Environ. Res. Lett. 14, 074005. https://doi.org/10.1088/1748-9326/ab17fb.
Qiao, L., Wang, X., Smith, P., Fan, J., Lu, Y., Emmett, B., Li, R., Dorling, S., Chen, H., Liu, S., Benton, T.G., Wang, Y., Ma, Y., Jiang, R., Zhang, F., Piao, S., Müller, C., Yang, H., Hao, Y., Li, W., Fan, M., 2022. Soil quality both increases crop production and improves resilience to climate change. Nat. Clim. Change 12, 574–580. https://doi.org/10.1038/s41558-022-01376-8.
Rao, J.M., 1989. Agricultural supply response: a survey. Agric. Econ. 3, 1–22. https://doi.org/10.1111/j.1574-0862.1989.tb00068.x.
Ray, D.K., Gerber, J.S., MacDonald, G.K., West, P.C., 2015. Climate variation explains a third of global crop yield variability. Nat. Commun. 6, 5989. https://doi.org/10.1038/ncomms6989.
Reidsma, P., Ewert, F., Lansink, A.O., Leemans, R., 2010. Adaptation to climate change and climate variability in european agriculture: the importance of farm level responses. Eur. J. Agron. 32, 91–102. https://doi.org/10.1016/j.eja.2009.06.003.
Rezaei, E.E., Webber, H., Asseng, S., Boote, K., Durand, J.L., Ewert, F., Martre, P., MacCarthy, D.S., 2023. Climate change impacts on crop yields. Nat. Rev. Earth Environ. 4, 831–846. https://doi.org/10.1038/s43017-023-00491-0.
Ritzel, C., von Ow, A., 2023. Swiss food security 2023: current events and trends. Agrar. Schweiz 167, 1–32. https://doi.org/10.34776/as167g.
Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A.C., Müller, C., Arneth, A., Boote, K.J., Folberth, C., Glotter, M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T.A.M., Schmid, E., Stehfest, E., Yang, H., Jones, J.W., 2014. Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proc. Natl. Acad. Sci. USA 111, 3268–3273. https://doi.org/10.1073/pnas.1222463110.
San José, R., Pérez, J.L., González, R.M., Pecci, J., Garzón, A., Palacios, M., 2016. Impacts of the 4.5 and 8.5 RCP global climate scenarios on urban meteorology and air quality: application to Madrid, Antwerp, Milan, Helsinki and London. J. Comput. Appl. Math. 293, 192–207. https://doi.org/10.1016/j.cam.2015.04.024.
Sansoulet, J., Pattey, E., Kröbel, R., Grant, B., Smith, W., Jégo, G., Desjardins, R.L., Tremblay, N., Tremblay, G., 2014. Comparing the performance of the STICS, DNDC, and DayCent models for predicting n uptake and biomass of spring wheat in eastern Canada. Field Crops Res 156, 135–150. https://doi.org/10.1016/j.fcr.2013.11.010.
Saxton, K.E., Rawls, W.J., 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Sci. Soc. Am. J. 70, 1567–1578. https://doi.org/10.2136/sssaj2005.0117.
Schauberger, B., Archontoulis, S., Arneth, A., Balkovic, J., Ciais, P., Deryng, D., Elliott, J., Folberth, C., Khabarov, N., Müller, C., Pugh, T.A.M., Rolinski, S., Schaphoff, S., Schmid, E., Wang, X., Schlenker, W., Frieler, K., 2017. Consistent negative response of US crops to high temperatures in observations and crop models. Nat. Commun. 8, 13931. https://doi.org/10.1038/ncomms13931.
Schmitt, K., 2024. Less nutritious crops: another result of rising CO2. Hopkins Bloomberg Public Health (accessed 28 May 2025). https://magazine.publichealth.jhu.edu/2024/less-nutritious-crops-another-result-rising-co2.
Schmitt, J., Offermann, F., Söder, M., Frühauf, C., Finger, R., 2022. Extreme weather events cause significant crop yield losses at the farm level in German agriculture. Food Policy 112, 102359. https://doi.org/10.1016/j.foodpol.2022.102359.
Schüepp, M., Gensler, G., 1980. Klimaregionen der schweiz (Climate regions of Switzerland). In: Müller, G. (Ed.), Die Beobachtungsnetze der Schweizerischen Meteorologischen Anstalt (The observation networks of the Swiss Meteorological Service). Arbeitsberichte der Schweizerischen Meteorologischen Anstalt, Nr. 93 (Work reports of the Swiss Meteorological Institute No. 93). Swiss Meteorological Institute. Zürich, Switzerland (accessed 15 October 2024). https://www.meteoschweiz.admin.ch/service-und-publikationen/publikationen/berichte-und-bulletins/1980/die-beobachtungsnetze-der-schweizerischen-meteorologischen-ansta.html.
Smith, W.N., Grant, B.B., Desjardins, R.L., Kroebel, R., Li, C., Qian, B., Worth, D.E., McConkey, B.G., Drury, C.F., 2013. Assessing the effects of climate change on crop production and GHG emissions in Canada. Agric. Ecosyst. Environ. 179, 139–150. https://doi.org/10.1016/j.agee.2013.08.015.
Steen, M., Bergland, O., Gjølberg, O., 2023. Climate change and grain price volatility: empirical evidence for corn and wheat 1971–2019. Commodities 2, 1–12. https://doi.org/10.3390/commodities2010001.
Stella, T., Webber, H., Eyshi Rezaei, E., Asseng, S., Martre, P., Dueri, S., Rafael Guarin, J., Pequeno, D.N.L., Calderini, D.F., Reynolds, M., Molero, G., Miralles, D., Garcia, G., Slafer, G., Giunta, F., Kim, Y.-U., Wang, C., Ruane, A.C., Ewert, F., 2023. Wheat crop traits conferring high yield potential May also improve yield stability under climate change. silico Plants 5, 1–16. https://doi.org/10.1093/insilicoplants/diad013.
Stumpf, F., Behrens, T., Keller, A., 2021. Faktenblatt Schweiz. Bodeneigenschaftskarten Version 1. Kompet. Boden (KOBO) Zollikofen Switz.
Su, F., Liu, Y., Chen, S.J., Fahad, S., 2023. Towards the impact of economic policy uncertainty on food security: introducing a comprehensive heterogeneous framework for assessment. J. Clean. Prod. 386, 135792. https://doi.org/10.1016/j.jclepro.2022.135792.
SWISSINFO, 2025. Initiat. a more selfsufficient Swiss Food Sect. Submitt. https://www.swissinfo.ch/eng/swiss-politics/initiative-for-a-more-self-sufficient-swiss-food-sector-submitted/86976743 (accessed 26 May 2025).
Tadesse, G., Algieri, B., Kalkuhl, M., von Braun, J., 2014. Drivers and triggers of international food price spikes and volatility. Food Policy 47, 117–128. https://doi.org/10.1016/j.foodpol.2013.08.014.
Thomasson, E., 2025. Extreme weather to prompt more food price spikes in 2025, experts predict. Green. Cent. Bank. https://greencentralbanking.com/2025/02/19/extreme-weather-food-prices-202 (accessed15 May 2025).
Tootoonchi, F., Bergkvist, G., Vico, G., 2025. Warmer growing seasons improve cereal yields in Northern Europe only with increasing precipitation. EGUsphere [Prepr.] 1–30. https://doi.org/10.5194/egusphere-2025-1982.
Vogel, E., Donat, M.G., Alexander, L.V., Meinshausen, M., Ray, D.K., Karoly, D., Meinshausen, N., Frieler, K., 2019. The effects of climate extremes on global agricultural yields. Environ. Res. Lett. 14, 054010. https://doi.org/10.1088/1748-9326/ab154b.
Walker, A.P., De Kauwe, M.G., Bastos, A., Belmecheri, S., Georgiou, K., Keeling, R.F., McMahon, S.M., Medlyn, B.E., Moore, D.J., Norby, R.J., 2021. Integrating the evidence for a terrestrial carbon sink caused by increasing atmospheric CO_2. N. Phytol. 229, 2413–2445. https://doi.org/10.1111/nph.16866.
Wang, H., He, Y., Qian, B., McConkey, B., Cutforth, H., McCaig, T., McLeod, G., Zentner, R., DePauw, R., Lemke, R., Brandt, K., Liu, T., Qin, X., White, J., Hunt, T., Hoogenboom, G., 2012. Climate change and biofuel wheat: a case study of Southern Saskatchewan. Can. J. Plant Sci. 92, 421–425. https://doi.org/10.4141/cjps2011-192.

Wang, H., Liu, H., Wang, D., 2022. Agricultural insurance, climate change, and food security: evidence from Chinese farmers. Sustainability 14, 9493. https://doi.org/10.3390/su14159493.
Webber, H., Ewert, F., Olesen, J.E., Müller, C., Fronzek, S., Ruane, A.C., Bourgault, M., Martre, P., Ababaei, B., Bindi, M., Ferrise, R., Finger, R., Fodor, N., Gabaldón-Leal, C., Gaiser, T., Jabloun, M., Kersebaum, K.-C., Lizaso, J.I., Lorite, I.J., Manceau, L., Moriondo, M., Nendel, C., Rodríguez, A., Ruiz-Ramos, M., Semenov, M. A., Siebert, S., Stella, T., Stratonovitch, P., Trombi, G., Wallach, D., 2018. Diverging importance of drought stress for maize and winter wheat in Europe. Nat. Commun. 9, 4249. https://doi.org/10.1038/s41467-018-06525-2.
Webber, H., Zhao, G., Wolf, J., Britz, W., Vries, Wd, Gaiser, T., Hoffmann, H., Ewert, F., 2015. Climate change impacts on european crop yields: do we need to consider nitrogen limitation? Eur. J. Agron. 71, 123–134. https://doi.org/10.1016/j.eja.2015.09.002.
White, H.J., Caplat, P., Emmerson, M.C., Yearsley, J.M., 2021. Predicting future stability of ecosystem functioning under climate change. Agric. Ecosyst. Environ. 320, 107600. https://doi.org/10.1016/j.agee.2021.107600.
Wösten, J.H.M., Lilly, A., Nemes, A., Le Bas, C., 1999. Development and use of a database of hydraulic properties of european soils. Geoderma 90, 169–185. https://doi.org/10.1016/S0016-7061(98)00132-3.
Wright, B.D., 2011. The economics of grain price volatility. Appl. Econ. Perspect. Policy 33, 32–58. https://doi.org/10.1093/aepp/ppq033.
WSL, 2023. NFI knowledge about the Swiss forest. Swiss Federal Institute for Forest, Snow and Landscape Research (accessed 10 September 2024). https://www.lfi.ch/index-en.php.