Projecting Climate Change Impacts on Winter Wheat Growth in Switzerland

Calibrating the WoFoSt Crop Simulation Model

Master Thesis

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Abstract

Climate change has impacted winter wheat growth in several ways and precise modelling studies are required to understand difficulties in future crop cultivation. Using the WoFoSt crop simulation model and climate projections for the 21st century, this study estimated the impact of climate change on winter wheat growth for the locations Changins and Reckenholz in Switzerland under RCP 4.5 and RCP 8.5. In both locations, considerable phenological shifts were projected under RCP 8.5, with average heading dates shifting forward by 22.2 days in Reckenholz and 24.4 days in Changins at the end of the century. Average maturity dates in this scenario shifted forward by 24.4 days and 25.5 days respectively. Smaller forward shifts were projected under RCP4.5, where heading dates shifted by 9.8 days (Reckenholz) and 11.1 days (Changins), while maturity dates shifted by 10.5 days (Reckenholz) and 10.9 days (Changins). With regards to future yield levels, this study found larger decreases of winter wheat yield in the higher emission scenario (Reckenholz: -17.91%, Changins: -23.85%) than the low emission scenario (Reckenholz: -4.16%, Changins: -6.04%) at the end of the century. However, the modelled impact of higher ambient CO2 concentrations more than offset this yield reduction, resulting in increased yield levels of up to 26.51% (Reckenholz) and 43.95% (Changins). Impact estimates of climate change on drought stress experienced by winter wheat were insignificant but showed differences in drought stress levels depending on soil type. Our findings indicate that winter wheat cultivation in Switzerland is strongly impacted by climate change, with a strong dependency on which representative concentration pathway the world will follow.

Contents:

1. Introduction

Climate change is a serious threat to global food security. Warming, changes in precipitation patterns, and more frequent extreme climatic events are some of the factors that have already impacted crop yields and are projected to continue doing so (IPCC, 2019). Winter wheat (*Triticum Aestivum)* is an essential food crop and accounts for about 80% of global wheat production (Franch et al., 2015). It is a major food crop that plays an important role in Swiss food and fodder production. In 2015, wheat for human consumption covered 53% of land used for cereal production in Switzerland (Bundesamt für Statistik, 2017).

Several studies have investigated the impacts of climate change on winter wheat growth. Under climate change, winter wheat phenology is predicted to advance by 2-3 weeks by the end of the century (Gouache et al., 2012), which can shift sensitive growing phases away from periods of heat and drought stress (Holzkämper et al., 2015; Semenov et al., 2011; Rogger et al., 2021; Torriani et al., 2007). However, a shorter phenology is likely to cause reductions in yield levels, most notably by giving the crop less time to intercept radiation during the maturation phase (Semenov et al., 2011). Beyond phenology shifts under climate change, rising temperatures, elevated CO2 concentrations, as well as shifts in rainfall patterns, are likely to affect agricultural production potentials (Ludwig et al., 2010). For winter wheat it has been shown that not drought stress, but rather the magnitude and frequency of heat stress periods will cause reductions in yield levels as the century progresses (Semenov et al., 2011; Rogger et al., 2021; Mishra et al., 2015). The crop is particularly sensitive to heat stress during heading and in the weeks thereafter (Rogger et al., 2021; Holzkämper et al., 2015). Rogger et al. (2021) find that yield reductions of 10% or more already occur if the crop experiences mild heat stress during grain filling (10-20 days after heading). Finally, climate change does present winter wheat cultivators with the potential for increased yield in the form of CO2 fertilization (Torriani et al., 2007). Torriani et al. (2007) explain that higher levels of CO2 affect C3 plants like winter wheat in the following ways: direct stimulation of photosynthesis, increased levels of transpiration, and increased water use efficiency. However, they also find that the increase in potential mean yield because of higher CO2 levels comes at the cost of increased variability in grain yield. Similarly, Gouache et al. (2012) find that the interaction of temperature and CO2 remains the largest source of uncertainty regarding future yield levels.

This variability and uncertainty mean that in a warming climate, adapting to local climatic conditions and understanding the vulnerabilities of winter wheat becomes critical. While large scale studies can predict large scale trends in crop productivity, location- and crop-specific studies are required to understand local crop-specific responses as well as derive possible adaptation possibilities (Torriani et al., 2007). Switzerland is a brilliant example of the necessity of location specific studies as it lies in between predictions for increased precipitation levels in northern Europe and decreased levels of precipitation in southern Europe (Fischer et al., 2011). In Switzerland, previous crop model simulation studies have explored the impacts of climate change on winter wheat, mostly based on the crop models cropsyst and SWAT (Paluoso et al., 2011; Torriani et al., 2007). Impact estimates are largely consistent across these studies but considering that climate impact model uncertainty can play a considerable role in climate impact studies (Asseng et al., 2015), studies based on alternative approaches are necessary to either increase confidence in previous findings or to highlight needs for impact model improvements, where estimates diverge.

The aim of this study was thus (i) to evaluate impacts of climate change on winter wheat productivity in Switzerland based on the crop model WoFoSt, thus providing a complement to previous climate change impact assessments for winter wheat in Switzerland, and (ii) to evaluate the suitability of WoFoSt for simulating winter wheat growth and productivity at different locations in Switzerland.

2. Data

To calibrate and validate the WoFoSt crop simulation model for Switzerland, different forms of data were needed. The following types of observed data were used: Weather, phenology timing, winter wheat yield, soil content, and leaf area index. Furthermore, this study required projected climate data for climate change projections under RCP 4.5 and RCP 8.5.

2.1 Climate and crop observation data

2.1.1 Climate

This study aimed to simulate winter wheat growth for the following locations in Switzerland: Reckenholz (REH) (Latitude: 47.43°; Longitude: 8.52°; Height: 460m), Changins (CGI) (Latitude: 46.4°; Longitude: 6.23°; Height: 458m), Neuchatel (NEU) (Latitude: 47.00°; Longitude: 6.57°; Height: 485m), Wynau (WYN) (Latitude: 47.25°; Longitude: 7.78°; Height: 422m), Schaffhausen (SHA) (Latitude: 47.68°; Longitude: 8.62°; Height: 438m). Each of these locations can be found in the following map.

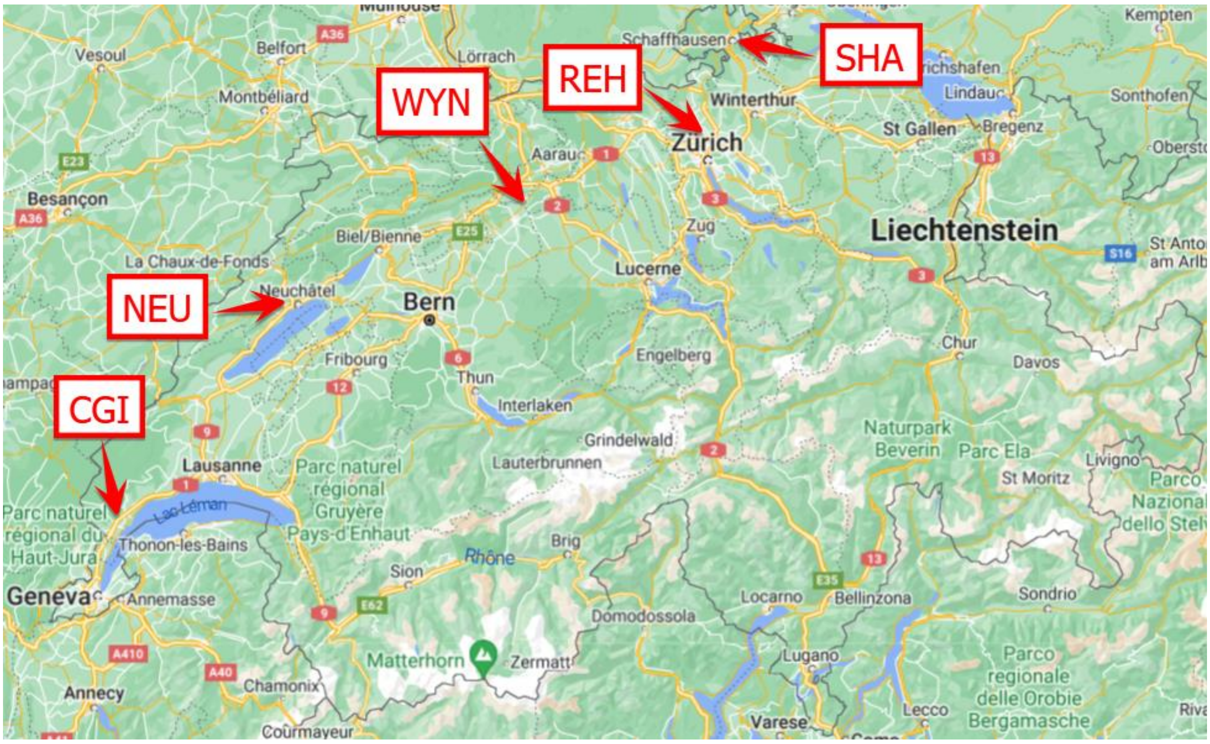


Fig. 1: Map of Switzerland, including marked study locations, taken from Google maps (n.d.).

These five locations present a range across the Swiss plateau. To simulate crop growth for these areas in WoFoSt, the following daily weather data was taken from weather stations operated by MeteoSwiss from 1989 to 2017 at each of the mentioned locations: mean global radiation [W/m²], min/max air temperature 2m above ground [°C], total precipitation [mm], min/max/mean relative air humidity 2m above ground [%], and mean wind speed [m/s]. The weather data was transformed to the required CABO-format before being used in WoFoSt.

2.1.2 Phenology

For model calibration, time series data on phenological stages containing sowing, flowering, and harvesting dates were available from Changins, for the *Arina* wheat variety from the official variety testing trials of the Swiss federal agricultural research institute Agroscope. The difference in harvest date and maturity date was assumed to be minimal. Due to the proximity of the locations, Changins is the only source of phenological data used for calibration. The phenological development of winter wheat in the other locations was assumed to be similar.

2.1.3 Yield

Yield data [kg/ha] from 1989 until 2017 taken from the farm accountancy data network of Switzerland (FAT) for Reckenholz and Changins was used to calibrate the yield simulation of WoFoSt. The data was averaged within a 15-kilometre radius around the climate station. Additionally, yields from Neuchatel, Wynau, and Schaffhausen from the same timeframe were used to validate the resulting model and check for possible transferability of simulations across different areas in Switzerland.

2.2 Detailed Reference Data

Detailed model reference data were available from the lysimeter facility at Zürich Reckenholz. The lysimeters 5, 10 and 11 in Reckenholz were used for weekly leaf area index (LAI) measurements as well as soil water content measurements. The planted winter wheat variety in 2022 was *Montalbano.* The lysimeters can be seen in following picture:

Fig. 2: Lysimeter setup in Reckenholz; picture taken on the 13.05.2022. Front left: lysimeter 5; front right: lysimeter 11; back right: lysimeter 10

For the field season of 2022 additional measurements of LAI were taken. LAI data for each lysimeter was obtained weekly from the growth stage BBCH31 onwards with a LAI-2200C plant canopy analyser. For this method, the LAI-2200C requires one measurement of sunlight influx above the canopy, and multiple below the canopy. In this study, each measurement consisted of six below measurements per lysimeter. The angle and position of the LAI-2200C during the below measurements are shown in figure 3. After collecting the LAI data, it was corrected for scattering in the FV2200 software.

Fig 3: Lysimeter 11 with LAI measurement markings, picture taken on the 13.05.2022.

This study used multiple different types of soil input data. While the calibration of the crop growth model was performed with the most fitting WoFoSt soil file EC3, soil data from the lysimeters in Reckenholz was needed to complete the subsequent validation. The three lysimeters exhibited differences in soil types as well as management. They were filled with two different soil types: soil taken from the Grafenried region and soil taken from the Reckenholz region. Lysimeter number 10 (back right) was filled with soil from Grafenried. The winter wheat was planted closely together, and other vegetation was allowed to grow on this plot. Lysimeter number 5 (front left) was filled with soil from Reckenholz, and the winter wheat was planted a lot less densely. No other vegetation is growing on this plot. Finally, lysimeter number 11 (front right) was filled with Reckenholz soil, with densely planted winter wheat and no further vegetation. Each lysimeter was fertilized three times during the 2022 growing season. Lysimeters 5 and 11 underwent the same treatment. They were fertilized with mineral fertilizer on the 29.03.2022 (70kg N/ha), the 12.04.2022 (30kg N/ha) and the 05.05.2022 (40kg N/ha). Lysimeter 10 was fertilized with slurry, on the following dates: 25.03.2022 (64.4kg N/ha), 12.04.2022 (48.3kg N/ha), 05.05.2022 (27.3kg N/ha).

The soil data used in this study is taken directly from these lysimeters. The following two tables show the weighted soil layer contents for Grafenried and Reckenholz soil in percent, relative to the thickness of the layer. In a subsequent step, the soil data was then aggregated across layers to create table 3.

Grafenried soil:

Table 1: weighted average of soil content of the Grafenried region. Variables: Depth upper/lower [cm]: upper and lower bound of soil layer; CACO3: Calcium Carbonate content in %; Humus: Humus content in %; USCLAY: Clay content in %; USSILT: Silt content in %; USSAND: Sand content in %; PH_H20: PH content of the soil measured in water; PH_CACL2: PH content of the soil measured calcium chloride; OC: Organic carbon content in %.

Depth upper[cm]	Depth lower[cm]	CACO3 [%]	Humus [%]	USCLAY [%]	USSILT [%]	USSAND [%]	PH_H20	PH_CACL2	OC [%]
0	5	0.0037	0.063	0.5926	1.1852	1.8889	0.2556	0.2333	0.0366
5	25	0.0148	0.2519	2.3704	4.7407	7.5556	1.0222	0.9333	0.1464
25	32	0	0.0187	1.037	1.3481	2.7481	0.3422	0.3007	0.0109
32	65	0	0.088	4.8889	6.3556	12.9556	1.6133	1.4178	0.0512
65	85	0	0.0237	2.6667	3.5556	8.5926	0.9926	0.8444	0.0138
85	110	0	0.0296	3.3333	4.4444	10.7407	1.2407	1.0556	0.0172
110	135	0	0.0148	2.963	5	10.5556	1.2593	1.0926	0.0086

Reckenholz soil:

Table 2: weighted average of soil content of the Reckenholz region. Variables: Depth upper/lower [cm]: upper and lower bound of soil layer; CACO3: Calcium Carbonate content in %; Humus: Humus content in %; USCLAY: Clay content in %; USSILT: Silt content in %; USSAND: Sand content in %; PH_H20: PH content of the soil measured in water; PH_CACL2: PH content of the soil measured calcium chloride; OC: Organic carbon content in %.

Depth upper[cm]	Depth lower[cm]	CACO3 [%]	Humus [%]	USCLAY [%]	USSILT [%]	USSAND [%]	PH_H20	PH_CACL2	OC [%]
0	5	0.0037	0.0941	0.9259	1.8519	0.9259	0.2519	0.237	0.0547
5	25	0.0148	0.3763	3.7037	7.4074	3.7037	1.0074	0.9481	0.2188
25	32	0.0104	0.0975	1.2444	2.8	1.1407	0.3681	0.3422	0.0567
32	65	0.0244	0.1809	7.5778	12.222	4.6444	1.76	1.5889	0.1052
65	85	0.0148	0.0815	4.8889	6.8148	3.1111	1.1111	0.9778	0.0474
85	110	5.9556	0.0267	2.8148	9.037	2.963	1.2741	1.1407	0.0155
110	135	12.089	0.0089	4	14.444	3.7778	1.9111	1.7333	0.0052

Table 3: Weighted aggregated soil content layer information based on soil content data from table 1 and 2. Variables: Depth upper/lower [cm]: upper and lower bound of soil layer; CACO3: Calcium Carbonate content in %; Humus: Humus content in %; USCLAY: Clay content in %; USSILT: Silt content in %; USSAND: Sand content in %; PH_H20: PH content of the soil measured in water; PH_CACL2: PH content of the soil measured calcium chloride; OC: Organic carbon content in %.

Location	**CACO3 [%]**	**Humus [%]**	**USCLAY [%]**	**USSILT [%]**	**USSAND [%]**	**PH_H20**	**PH_CACL2**	**OC [%]**
Grafenried	0.00265	0.06995	2.55026	3.80423	7.86243	6.73	5.88	0.04067
Reckenholz	2.58751	0.12368	3.59365	7.79683	2.89524	7.68	6.97	0.07191

The main differences between these two soil types were that the Grafenried soil exhibited higher levels of sand content, as opposed to the soil from Reckenholz, which contained a higher percentage of calcium, humus, clay, silt, and organic carbon.

To accurately simulate winter wheat growth for the three lysimeters, the data from the two different soils had to meet the data input requirements of WoFoSt. WoFoSt soil files require the soil moisture content at three different points: at wilting point, at field capacity, and at saturation. Additionally, the files hold data regarding the critical soil air content for aeration, and the hydraulic conductivity of saturated soil. To this end, it was necessary to apply a pedotransfer function to the observed data. In this study, the recently published package “euptf2” (Szabó et al., 2021; Weber et al., 2020; R Core Team, 2021) was used to derive these parameters based on available information of soil texture and organic carbon content. This was done for the two soil types from tables 1 and 2, in two different ways.

Grafenried 1, Reckenholz 1, Grafenried 2, and Reckenholz 2 are soil files that were created with the same data and the same “euptf2” R package. The difference between soil types 1 and 2 for Reckenholz and Grafenried lies in the method of aggregation. Grafenried 1 and Reckenholz 1 were parameterized with the pedotransfer function for each layer until a depth of 110cm first, and consequently aggregated across these layer parameters to create the soil file. Reckenholz 2 and Grafenried 2 were created by aggregating weighted soil layer information until a depth of 135cm first (table 3), before being parameterized with the pedotransfer of the “euptf2” function in R (Szabó et al., 2021; Weber et al. 2020; R Core Team, 2021).

To summarize, this study used five different soil parameter sets as inputs for WoFoSt. The base WoFoSt soil file EC3 was used for the calibration of the model. For the subsequent validation of the crop growth model, as well as the projection of drought stress under different climate change scenarios, the soil files Grafenried 1, Grafenried 2, Reckenholz 1, as well as Reckenholz 2 were used.

2.3 Climate projections

Once the calibration of the WoFoSt crop model was completed using the previously mentioned data, this study ultimately aimed to predict winter wheat growth in Switzerland for the 21st century. To this end, climate projection data from the CH2018 Swiss Climate Change Scenarios for RCP2.6, RCP4.5 and RCP8.5 was used (CH2018, 2018). The following GCM-RCM-model chains were used:

- SMHI-RCA_CCCMA_EUR44
- SMHI-RCA_ECEARTH_EUR44
- SMHI-RCA_HADGEM_EUR44
- DMI-HIRHAM_ECEARTH_EUR44
- DMI-HIRHAM_ECEARTH_EUR11
- KNMI-RACMO_HADGEM_EUR44
- KNMI-RACMO_ECEARTH_EUR44

As before, the projection data used to create CABO-files consisted of: mean global radiation [W/m²], min/max air temperature 2m above ground [°C], total precipitation [mm], mean relative air humidity 2m above ground [%], and mean wind speed [m/s].

3. Methods

3.1 WoFoSt functionality

To estimate winter wheat production in Switzerland, this study calibrated and applied the crop growth simulation model WoFoSt (WoFoSt Control Centre ver. 2.1). The model can simulate the production of crops under ideal conditions, as well as water and nutrient limited production scenarios.

The crop growth simulation occurs in four steps: (1) assimilation and respiration, (2) phenological development, (3) partitioning of dry matter and (4) transpiration (De wit et al. 2021). Stage (1) calculates the gross CO2 assimilation rate of the crop, based on the radiation the plant absorbs and its photosynthesis-light response curve. Stage (2) predicts the phenology by simulating the daily development rate of the plant as a function of temperature and day length (Wolf et al. 2011). In stage (3), after subtracting the respiration losses in stage (1) WoFoSt uses partitioning tables to divide the net assimilates to different plant organs throughout the growing cycle. The assimilates are distributed between roots, leaves, stems, and storage organs. The final stage (4) calculates transpiration from the crop to the atmosphere. WoFoSt does this by calculating transpiration for a reference crop, given the radiation level, vapor pressure deficit and wind speed. This reference value is subsequently adjusted for the simulated crop, depending on its water demands (De Wit et al. 2021).

The required inputs for WoFoSt simulations are daily weather data, soil characteristics, crop parameters, and management practices (Wolf et al. 2011).

3.2 Phenology calibration

A critical component of accurate crop growth simulation is phenology. Therefore, it was the first step of calibrating the WoFoSt model for winter wheat. WoFoSt simulated phenological development as a function of daylength as well as thermal time. Daylength was simulated with two inputs: optimum daylength (DLO), and critical daylength (DLC). For winter wheat (a long day crop), Optimal daylength was set to 14 hours, while critical daylength was set to 8 hours. These inputs were taken from the documentation of the python version of WoFoSt (De Wit, 2017) and remained the same throughout the calibration process.

Instead, the phenological calibration was performed by adapting the thermal time required to reach the flowering as well as the maturity date of the crop. Thermal time is the integral over time of the daily effective temperature after crop emergence. And “the daily effective temperature is the difference between the daily average temperature and a base temperature below which no development occurs" (De wit et al. 2021). For each growth day the model then divided the current thermal time by the thermal time required to reach flowering/maturity. The result of this division determines the development stage (DVS) in WoFoSt. The DVS is 0 at sowing, 1 at flowering and 2 at crop maturity. The model uses two thermal time parameters as inputs: TSUM1 and TSUM2. TSUM1 describes the thermal time required from emergence to reach the flowering stage, while TSUM2 describes the thermal time required from flowering to reach the maturity stage. Successful phenological calibration depended on finding the optimal values for these two inputs for a given location.

To this end, the program was run on its 'potential production' setting. This ensured that the crop grew stress-free and without impeding its phenological development. The program was run multiple times using meteorological data from Changins, while varying the TSUM1 and TSUM2 variables by steps of one within the plausible range of +/- 200 around the base value of 1000. Subsequently, the accuracy of the flowering as well as the maturity dates of each of these runs were evaluated. This was performed by minimizing the root mean squared difference between simulated and observed flowering and maturity dates in Changins from the years 2000 to 2018, using the following functions, taken from Ceglar et al. 2019.

$$f(x) = \sqrt{f(a) + f(m) + f(h)} \qquad f(a) = \frac{\sum_{i=1}^{n} w_i \cdot (a_{i,o} - a_{i,s})^2}{\sum_{i=1}^{n} w_i}$$

Fig. 4: Weighted mean squared differences formulas for optimal TSUM1 and TSUM2 calibration; taken from Ceglar et al. 2019. a: simulated/observed anthesis date; m: simulated/observed maturity date; h: simulated/observed harvest date (harvest and maturity date were assumed to be the same in this study); w: weights (assumed to be identical between anthesis and maturity =1)

This process was performed approximately 200 times before finding the optimal settings for simulating the phenology of winter wheat in Changins. The optimal setting for TSUM1 was found to be 974, while TSUM2 was set to 1012.

3.3 WoFoSt Crop Yield Simulation

After calibrating the phenological development of the winter wheat model, it was calibrated with regards to yield. This process was performed for the location Changins as well as the location Reckenholz. In this step, WoFoSt was run on the 'Water-limited production' setting.

This setting is more realistic. It simulates crop growth in the absence of irrigation, which is the typical method of growing winter wheat in a field.

The calibration was performed by running the WoFoSt crop simulation repeatedly, while changing specific variables in the crop file. In this study, WoFoSt was run 20,000 times for each location with different crop file inputs. The changes to these inputs were performed using Latin hypercube sampling in python. This method generates random samples of parameter values within bounds from a multidimensional distribution.

In accordance with the research of Boons-Prins et al. (1993) on winter wheat calibration in WoFoSt, the following variables were randomized with Latin hypercube sampling, within sensible bounds:

- Specific leaf area as a function of development stage (SLA)
- Maximum relative increase in leaf area index (RGRLAI)
- Life span of leaves growing at 35°C (SPAN)
- Maximum leaf CO_2-assimilation as a function of development stage (AMAXTB)

Additionally, the following two variables were also included in this process, as changing them showed positive effects on the accuracy of the model:

- Efficiency of conversion into storage organs (CVO)
- Relative increase in respiration rate per 10°C temperature increase (Q10)

After randomizing the variables for 20,000 runs in Reckenholz and Changins respectively, the resulting output files of each of these runs were then compared to the actual yield data for both locations. The performance of the simulated runs was evaluated using the goodness of fit function of the hydroGOF package in R (Zambrano-Bigiarini, 2020; R Core Team, 2021). This function requires a set of simulation data and a set of observed data that are of the same length as inputs. It then provides multiple values to evaluate the given data, including the Willmott index of agreement (d) (Willmott, 1981), the root mean squared error (RMSE), and the correlation (r). This information could then be used to make an informed decision on which run was considered the best and should be used in the subsequent steps. Once this step was completed, the model was considered calibrated for the given location.

3.4 Model validation

Following calibration, the model was validated for the year 2022, by using leaf area index (LAI) measurements, as well as soil water content (SWC) data from the lysimeters 5, 10, and 11 in Reckenholz of the 2022 growing season. The simulated LAI and SWC outputs used for validation of the model were taken from running the calibrated version of WoFoSt for 2022 in Reckenholz. Subsequently, the fit of the simulated and observed values was evaluated using the hydroGOF package in R (Zambrano-Bigiarini, 2020; R Core Team, 2021). Moreover, as a final validation step, this study used meteorological as well as yield data from Neuchatel, Schaffhausen, and Wynau. While the model was not specifically calibrated for these locations, it should be able to predict winter wheat growth to some extent. The calibrated models for each Changins and Reckenholz were run with the meteorological inputs of the three previously mentioned locations, and the index of agreement was subsequently evaluated.

3.5 Climate Change Scenario Projection

After WoFoSt was calibrated and validated, it could be applied to different climate change scenarios for both locations. The projection simulation ranged from the current day to the end of the 21st century, the year 2099. It was performed for two climate change scenarios, RCP 4.5, and RCP 8.5. This simulation gave insight into the future production of winter wheat, its phenological development, as well as potential water limitations during crop growth. The projections are created for the two locations Reckenholz and Changins.

The potential benefit and costs of CO2 fertilization had to be accounted for when simulating projections for a C3 plant such as winter wheat. Specifically in the high emission scenario RCP 8.5, where this study tested the case of the CO2 concentration reaching 720 parts per million by 2060-2080, and 1000 parts per million (ppm) towards the end of the century (2080-2099). To account for the effect of CO2 fertilization on winter wheat growth for RCP 8.5, the following model inputs were adapted based on the crop parameter file of Allard de Wit (De Wit, 2017), one of the creators of WoFoSt:

- Initial light use efficiency of CO2 assimilation of single leaves as a function of daily temperature (EFFTB)

- Correction factor for evapotranspiration in relation to the reference crop (CFET)
- Maximum leaf CO2-assimilation as a function of development stage (AMAXTB)

Table 4: Input values for the projection of winter wheat growth in the 21st century with the impact of CO2 fertilization for Reckenholz and Changins. CO2[ppm]: global atmospheric concentration of carbon dioxide in parts per million; AMAXTB: maximum leaf CO2 assimilation as a function of development stage; EFFTB: initial light use efficiency of CO2 assimilation of single leaves as a function of daily temperature; CFET: correction factor for evapotranspiration in relation to the reference crop.

Location	**CO2 [ppm]**	**AMAXTB**	**EFFTB**	**CFET**
Reckenholz	720	59.45108	0.4995	0.9
Reckenholz	1000	70.59817	0.4995	0.9
Changins	720	62.00014	0.4995	0.9
Changins	1000	73.62517	0.4995	0.9

While the changes in EFFTB and CFET were the same across the simulations, AMAX depended on the amount of CO2 in the atmosphere as well as the previous AMAX setting, which yielded different input values for Reckenholz and Changins. All other input factors remained unchanged from the calibration to simulate future crop production as accurately as possible.

4. Results

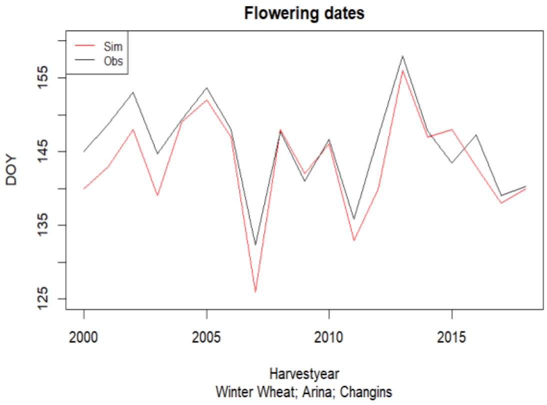
4.1 Model evaluation

After running WoFoSt a minimum of 20,000 times for each location in an attempt to find the ideal fit for each evaluation parameter, this section presents the findings regarding the accuracy of the phenology and yield simulations of the highest fit simulations.

4.1.1 Phenology

The results of the WoFoSt model calibration indicated high accuracy with regards to its phenology simulation. Both the flowering and maturity dates were found to be highly accurate when compared to the observed dates, with a Willmott index of agreement of d=0.92 for both. For flowering, the root mean squared error (RMSE) was 3.73 days, while the

RMSE for maturity was 3.43 days. The graphs below show the simulated phenology dates plotted against the observed dates from Changins.



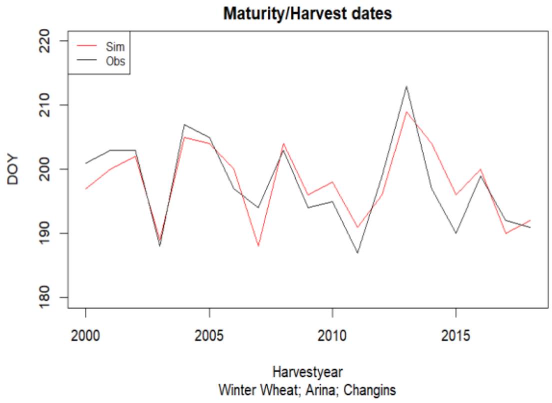


Fig. 5: Simulated (red) and observed (black) flowering and maturity dates for winter wheat variety "Arina" in Changins for harvest years 2000 to 2018. Left: flowering dates shown in day of year. Right: harvest dates shown in day of year. Harvest and maturity dates are assumed to be similar.

Overall, flowering tended to be simulated slightly early, while no trend was visible for maturity. These results were promising, as reliable phenology simulation provided a solid basis for yield calibration of the crop model. Moreover, the timing of flowering and the length of the growing season were of particular interest regarding the influence of climate change on crop yield and quality.

4.1.2 Yield

After 20.000 calibration runs with varying inputs, the simulation with the highest fit was chosen for each location. The table below shows the inputs for the two highest performing runs for each Reckenholz and Changins.

Table 5: Calibrated input values for Reckenholz and Changins. Run nr.: the simulation run that exhibited the highest index of agreement (d) of the 20.000 calibration runs; RGRLAI: maximum relative increase in leaf area index; SPAN: life span of leaves growing at 35°C; SLA: specific leaf area as function of development stage; AMAXTB: maximum leaf CO2 assimilation as a function of development stage; CVO: efficiency of conversion into storage organs; Q10: relative increase in respiration rate per 10°C temperature increase.

Location	**Run nr.**	**RGRLAI**	**SPAN**	**SLA**	**AMAXTB**	**CVO**	**Q10**
Reckenholz	12171	0.01436	35.20468	0.00196	37.15693	0.35785	1.43
Changins	7095	0.01367	35.16185	0.00133	38.75009	0.4375	1.75

Run number 12171 was the most accurate run for Reckenholz when comparing simulated yields to the yield observations from 1989 to 2017. The simulation exhibited an agreement index of d=0.67, with a RMSE of 450.89 [kg/ha], as well as a correlation of 0.46. The average yield level of the simulation was 5545.185 [kg/ha], while the mean observed yield in Reckenholz was 5575.941 [kg/ha]. The year 2016 was omitted from the evaluation for Reckenholz because the observed yield suffered from oxygen shortage. WoFoSt was not run to simulate oxygen shortage, so the results for this harvest year were not representative of the strength of the simulation.

For Changins, run number 7095 exhibited the highest evaluation of accuracy with regards to yield simulation. When compared to the observations from Changins from 2005 to 2015, the simulation showed an agreement index of d=0.76, a RMSE of 555.89 [kg/ha], as well as a correlation of 0.56. The average simulated yield amounted to 5344.182 [kg/ha], while the average observed yield levels for this timeframe were 5330.178 [kg/ha].

As can be seen in figure 6 below, both simulations fluctuated around the observed values. The most notable differences can be seen in the years 1990, 1999, and 2017 for Reckenholz. For Changins this was the case in 2005 and 2014.

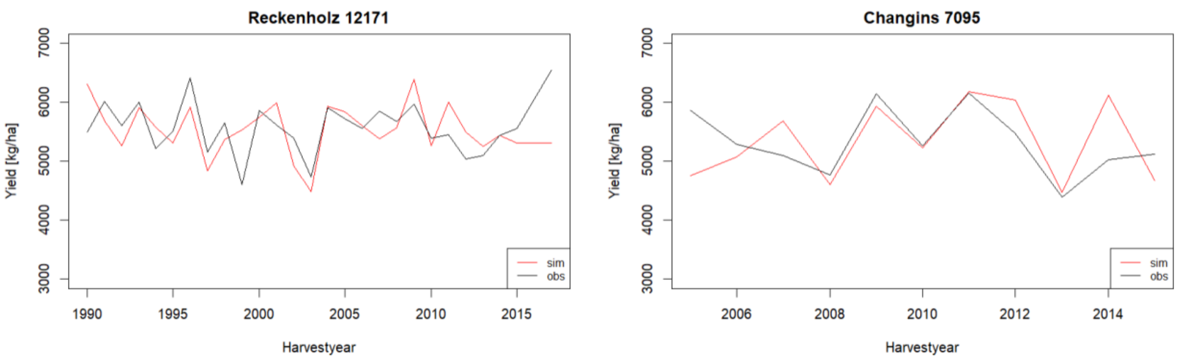


Fig. 6: Comparison of yield observations and yield of calibrated WoFoSt simulation runs for Reckenholz and Changins. Yield is shown in kg/ha for the respective observation timeframe. Left: Reckenholz simulation run 12171 yields (red), compared to observations from 1989 to 2017 (black). Right: Changins simulation run 7095 yields (red), compared to observations from 2005 to 2015 (black).

4.2 Validation

4.2.1 Yield:

In a first step of validation, we determined whether the 20.000 simulation runs showed trends regarding transferability between locations. To this end, the index of agreement value of each calibration run was plotted against the index of agreement of the respective calibration run when applied to another location.

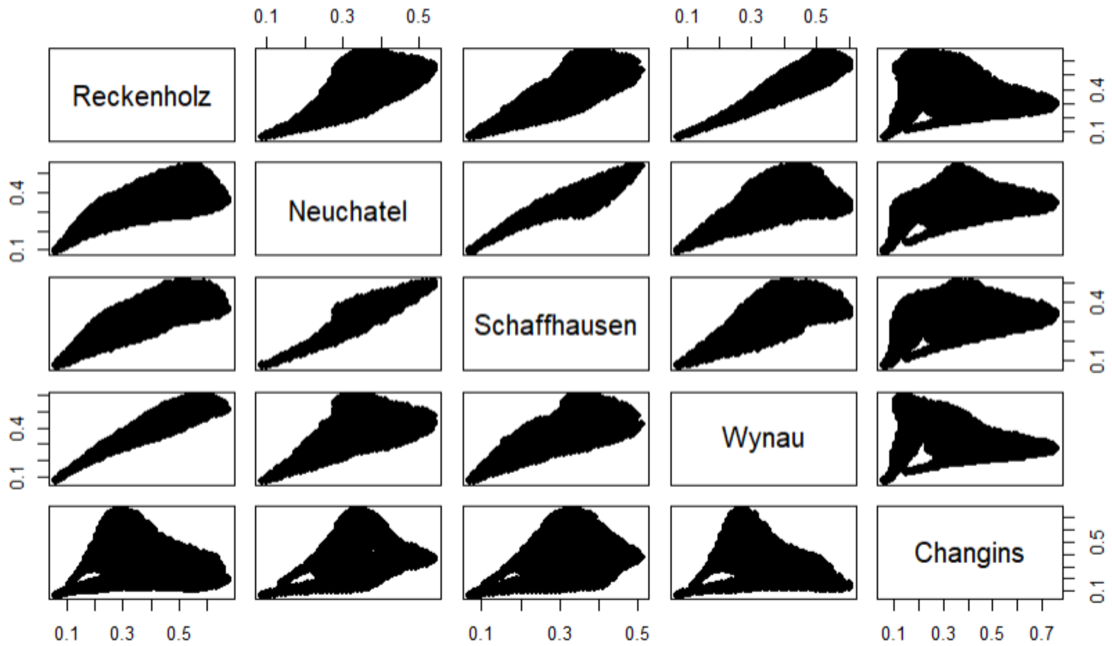


Fig 7: All location specific calibration index of agreement values (d) plotted against index of agreement values of calibration runs from each other location. This plot includes 20,000 index of agreement values for Reckenholz, Neuchatel, Schaffhausen, Wynau, and Changins.

While Reckenholz, Neuchatel, Schaffhausen and Wynau showed positive trends, no such trends could be seen when comparing Changins to the other locations. The simulation in Changins did reach high levels of agreement but did not transfer to other locations. While this could be explained to some degree by the difference in climatic conditions, this lack of transferability was surprising. To directly compare the suitability of the simulation runs with the highest index of agreement for each location, the following table shows the highest performing simulation for each location (shown in red) and how accurately that parameter set simulated winter wheat growth for the other locations.

Table 6: Index of agreement values (d) for different simulation runs, compared to observations for locations Reckenholz (REH), Changins (CGI), Neuchatel (NEU), Schaffhausen (SHA), and Wynau (WYN). The five chosen runs represent the simulations with the highest d value for each of the respective locations in order (shown in red).

Run nr.	REH	CGI	NEU	SHA	WYN
12171	0.67	0.20	0.37	0.37	0.51
7095	0.29	0.76	0.35	0.33	0.27
491	0.54	0.36	0.54	0.49	0.44
16327	0.53	0.37	0.54	0.51	0.42
8309	0.60	0.15	0.36	0.37	0.60

As can be seen in table 6, the different simulations exhibited different levels of transferability to other locations. For Reckenholz, the 12171 run was somewhat accurate for Wynau but lacked accuracy in Changins, Neuchatel and Schaffhausen. While run number 7095 was highly accurate in Changins, it did not transfer well to other locations. Although the highest index of agreement runs in Neuchatel and Schaffhausen exhibited slightly lower levels of the agreement index of 0.54 and 0.51, respectively, they exhibited a higher level of transferability to the other locations (d>0.35). Finally, simulation number 8309 simulated crop yield in Wynau and Reckenholz with the same accuracy, while it exhibited the smallest transferability to Changins an index of agreement of d=0.15.

4.2.2 Leaf Area Index (LAI):

The comparison of the LAI development in run number 12171 in Reckenholz for the year 2022 to measured LAI values for the lysimeters 5, 10 and 11 in Reckenholz is shown in the graphs below. The LAI development of the simulation when compared to the LAI development in lysimeter 5 showed the following evaluation values: d=0.79, a RMSE of 1.09 and a correlation of 0.8. For lysimeter 10 the simulation exhibited d=0.88, a RMSE of 0.83 and a correlation of 0.83. Finally, the simulation for lysimeter 11 showed an index of agreement value of 0.81, a RMSE of 0.90 and a correlation of 0.74.

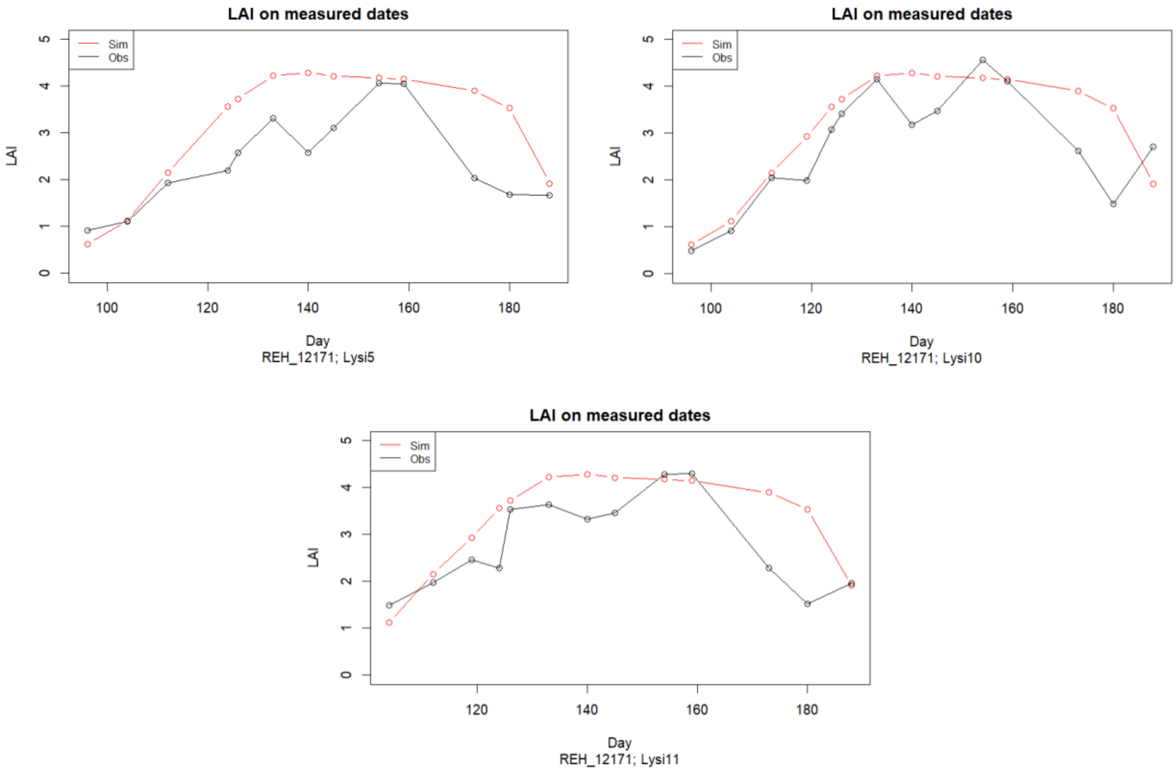


Fig 8, 9, 10: LAI development comparison for the growing season 2022. WoFoSt LAI simulation development is shown in red, measurements from the lysimeters 5 (top left), 10 (top right), and 11 (bottom) shown in black. Each point represents a day of LAI measurement, shown as day of year in 2022.

The simulated LAI developed evenly throughout the growing season, reaching a maximum at the beginning of the flowering stage around day 135 of the growing season. At this point, the slope of the LAI development became negative, and the LAI decreased until harvest. While the agreement index for the lysimeter 5 simulation was d=0.79, the observed LAI developed less evenly, and changed slope multiple times. Measurements in lysimeter 5 exhibited a lower LAI than simulated. Most notably from days 124 to 145, as well as from days 173 to 188. However, the observations did reach the simulated level of LAI on days 154 and 159.The simulated LAI development for lysimeter 10 showed the highest index of agreement (d=0.88). This is visible in the graph, as the level of LAI observations was closer to the simulated LAI values. Days 96, 104, 112, 133 and 159 of the simulation were very accurate; however, the observations exhibited a dip in LAI on days 140 and 145 of the year 2022.

Finally, the plotted measurements performed on lysimeter 11 developed similarly to Lysimeter 10. While not being as accurate in the pre flowering phase, the observations showed a less pronounced dip in LAI measurements during flowering, yielding an overall agreement index of d=0.81.

4.2.3 Soil water content:

The accuracy of the soil water content (SWC) simulation for the year 2022 was evaluated using the 12171 simulation for Reckenholz with five different soil profiles: EC3, Grafenried 1, Grafenried 2, Reckenholz 1, and Reckenholz 2. These soil profiles were used to simulate soil water content and were subsequently compared to the measured soil water content data of each of the lysimeters 5, 10 and 11 in Reckenholz. Each of the lysimeters measured soil water content at 4 depths: 10 cm, 30 cm, 60cm, and 90cm. Both lysimeters 5 and 11 with Reckenholz soil exhibit a higher SWC than the Grafenried soil in lysimeter 10, as can be seen in the following table.

Table 7: Mean measured soil water content for the first 200 days of 2022 at different depths in the lysimeters in Reckenholz. Each lysimeter has two frequency domain reflectometry sensors per depth level (10, 30, 60, 90. All measurements in cm^3 water per cm^3 soil. Reckenholz soil type is shown in black, Grafenried soil type in red.

	FDR 10	FDR 30	FDR 60	FDR 90
Lysimeter 5	0.291	0.330	0.391	0.377
Lysimeter 10	0.250	0.306	0.307	0.334
Lysimeter 11	0.254	0.353	0.337	0.378

To further illustrate this, the following three graphs show the development of the SWC for all three lysimeters.

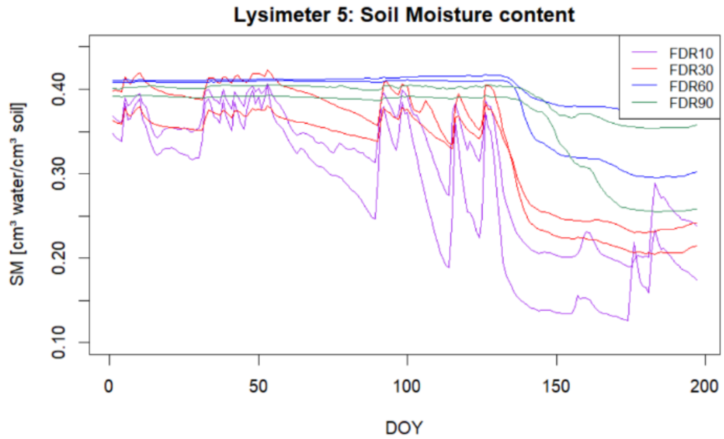


Fig. 11: Soil Moisture content observations for lysimeter 5 filled with soil from the Reckenholz area. FDR: Frequency domain reflectometry sensors placed in different depths. Each depth level: 10cm (purple), 30cm (red), 60cm (blue), 90cm (dark green) was measured by two sensors.

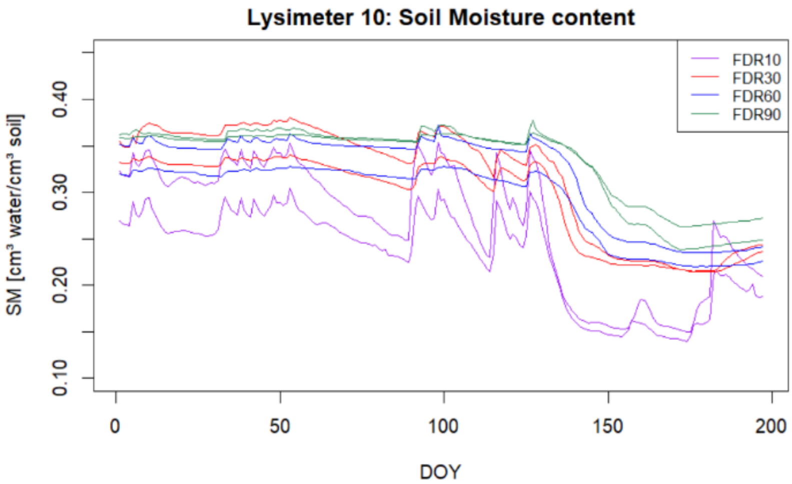


Fig. 12: Soil Moisture content observations for lysimeter 10 filled with soil from the Grafenried area. FDR: Frequency domain reflectometry sensors placed in different depths. Each depth level: 10cm (purple), 30cm (red), 60cm (blue), 90cm (dark green) was measured by two sensors.

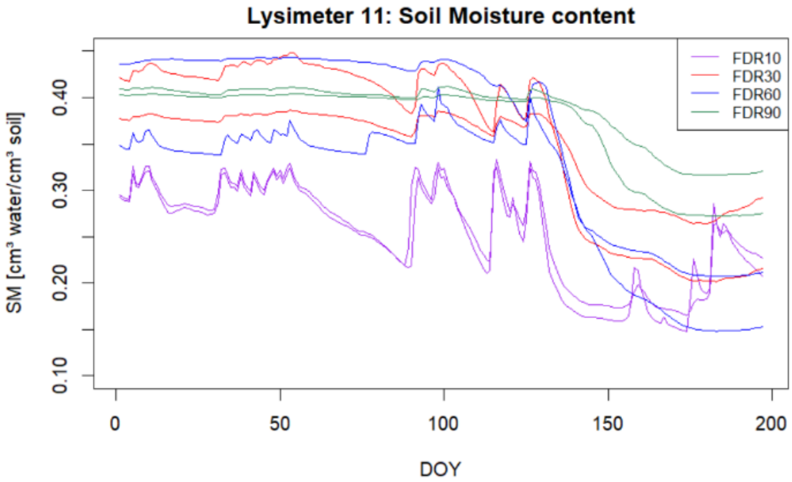


Fig. 13: Soil Moisture content observations for lysimeter 11 filled with soil from the Reckenholz area. FDR: Frequency domain reflectometry sensors placed in different depths. Each depth level: 10cm (purple), 30cm (red), 60cm (blue), 90cm (dark green) was measured by two sensors.

The soil moisture content of the lysimeters (table 7, Figures 11-13) was used to evaluate the accuracy of the soil water content simulation of the WoFoSt crop simulation model with differing soil inputs based on the Willmott index of agreement. The following table 8 shows these values:

Table 8: Index of agreement values (d) of soil water content for simulations using different soil files: EC3, Grafenried 1, Grafenried 2, Reckenholz 1, Reckenholz 2, compared to the mean soil water content observations of lysimeters 5, 10 and 11 in Reckenholz. X denotes soil files that were not compared to the observed soil water content data.

Lysimeter nr.	**EC3**	**Grafenried 1**	**Grafenried 2**	**Reckenholz 1**	**Reckenholz 2**
5	0.64	X	X	0.76	0.57
10	0.82	0.83	0.78	X	X
11	0.74	X	X	0.66	0.67

The soil water content simulations for lysimeter 5 proved to be most accurate when using the Reckenholz 1 soil type, with a d of 0.76. All three soil profiles simulated with an agreement index of over 0.77 for lysimeter 10. Not only did the fitting soil profile of Grafenried 1 provide an accurate simulation of the soil water content of the lysimeter, but so did the base WoFoSt file EC3, as well as Grafenried 2.

Contrary to expectations, lysimeter 11 did not exhibit the highest fit with soil data based on the Reckenholz area. The soil type with the highest index of agreement for lysimeter 11 was EC3 (d=0.74).

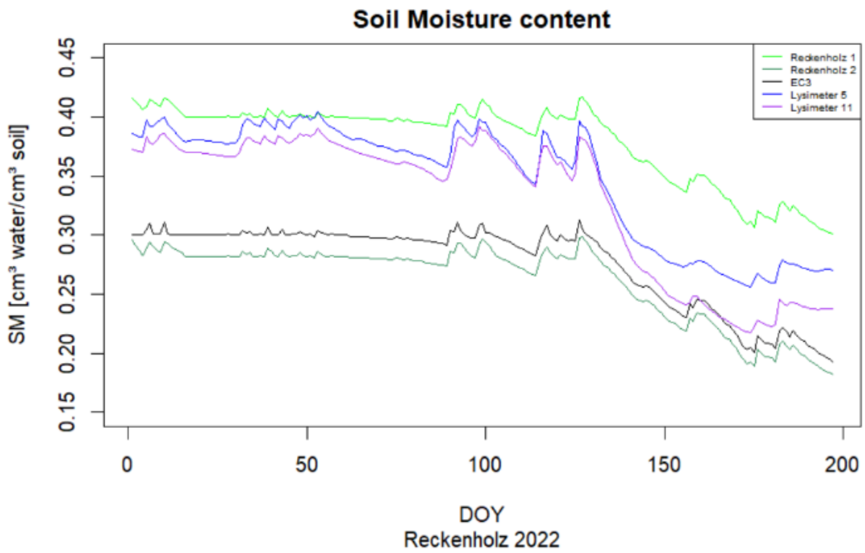


Fig 14: Soil Moisture content for soil simulations using soil types EC3 (black), Reckenholz 1 (green) and Reckenholz 2 (dark green). Lysimeter 5 and lysimeter 11 soil moisture content observations shown in blue and purple respectively. Soil moisture content shown in cm³ water/*cm³* soil for 2022.

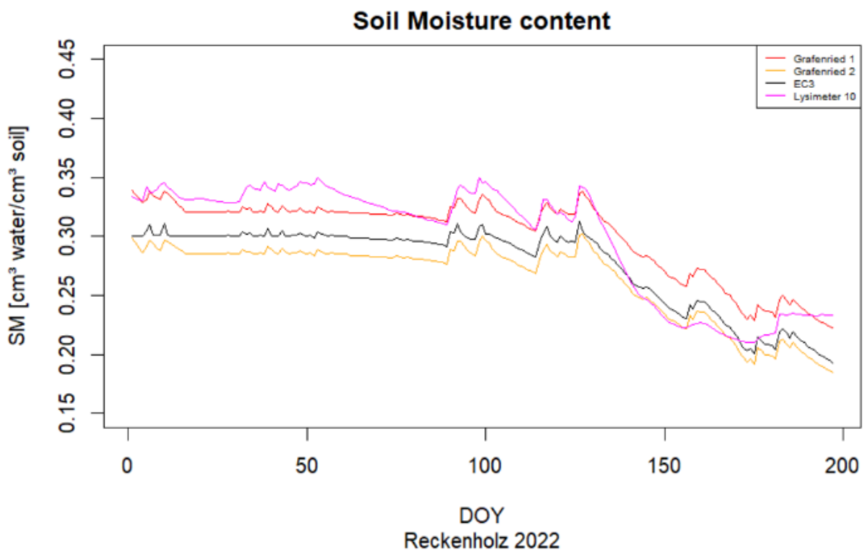


Fig 15: Soil Moisture content for soil simulations using soil types EC3 (black), Grafenried 1 (red) and Grafenried 2 (orange). Lysimeter 10 soil moisture content observations shown in pink. Soil moisture content shown in cm³ water/*cm³* soil for 2022.

Overall, figures 14 and 15 show that WoFoSt simulated soil water content development accurately over time. Until flowering at around day 135, the three observations developed very similar to the simulations. Past this point, the observations exhibited a stronger drop in Soil water content than the simulations. Nevertheless, the overall accuracy as indicated by the Willmott index of agreement was satisfactory, specifically for the Grafenried 1 soil. The WoFoSt soil file EC3 also performed very well, most notably when compared to lysimeters 10 and 11.

Figures 14 and 15 demonstrate the difference in the accuracy of Reckenholz and Grafenried type soil water content simulations. For Reckenholz, we could clearly see that the Reckenholz 2 soil profile underestimates the soil water content throughout the year 2022, while the Reckenholz 1 type developed more closely to the lysimeter observations pre flowering but overestimated the soil water content in the post flowering phase. The level of soil water content in the Grafenried soil simulation seen in figure 15 is more accurate. However, the similarity between the two figures is the change in accuracy before and after the beginning of flowering. All soil types predicted a lower decline in soil water content after flowering than lysimeter data.

Overall, WoFoSt achieved index of agreement values above 0.75 for multiple soil types. WoFoSt seemed to struggle with the change in soil water content during and after the flowering phase. The Grafenried 1 soil file was shown to reach the highest overall index of agreement (d=0.83) of the simulations.

4.3 Projections of winter wheat production

4.3.1 Phenology Projections

Based on the projected climate scenarios used in this study, significant shifts in winter wheat phenology were estimated to take place in the 21st century. However, the severity of these shifts depended on the representative concentration pathway the world could follow. To illustrate this, the plots below show the flowering and maturity dates for Reckenholz and Changins in RCP 8.5 as well as RCP 4.5. Each point represents the respective simulated phenology date, using the previously mentioned GCM-RCM-model chains as projection data.

Reckenholz:

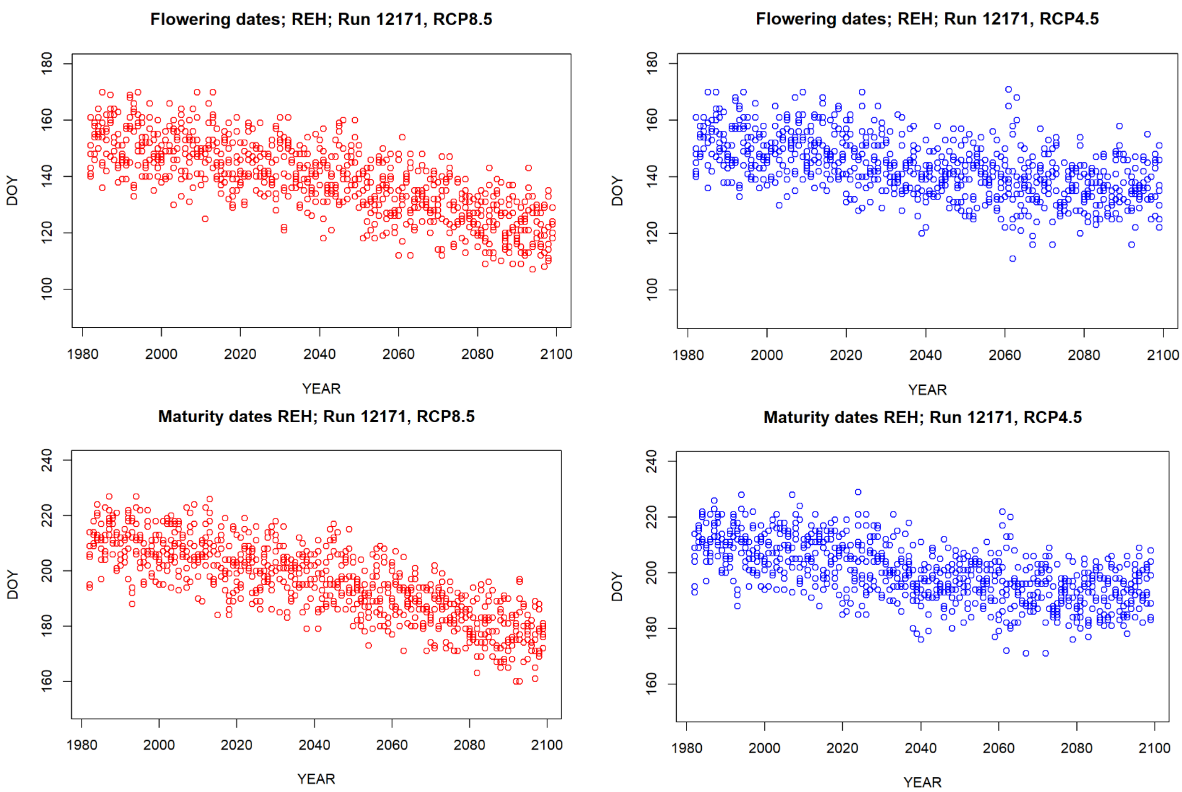


Fig. 16: Flowering and Maturity dates shown as day of year. Projections for Reckenholz run number 12171 under different climate change scenarios RCP 8.5 and RCP 4.5. Top left: flowering dates under RCP 8.5 (red), bottom left: maturity dates under RCP 8.5 (red), top right: flowering dates under RCP 4.5 (blue), bottom right: maturity dates under RCP 4.5 (blue)

In both scenarios for Reckenholz, flowering and maturity dates shifted forward. However, this shift was more evident in the higher emission scenario shown in red. In this scenario, mean flowering dates were predicted to shift forward by 22.2 days by the end of the century, from day 144.1 for the period 2020-2029 to day 121.9 in 2090-2099. Overall, the flowering dates shifted forward by 3.17 days per decade. Similarly, mean maturity dates shifted by 24.4 days, from day 201.7 in 2020-2029 to day 177.3 in 2090-2099. This amounted to a 2.11 days per decade shift in maturity timing. In this RCP 8.5 scenario, winter wheat was projected to flower approximately at the start of May and mature before the end of June.

In the lower emission scenario RCP 4.5 shown in blue, these shifts were less pronounced. In this case, mean flowering dates were simulated to shift forward by 9.8 days, from day 146.5 in 2020-2029 to 136.7 in 2090-2099. The mean maturity dates were simulated to shift forward by 10.5 days, from day 203.8 in 2020-2029 to day 193.3 in 2090-2099. RCP4.5 caused a 1.4 days per decade forward shift in flowering and a 1.5 days per decade forward shift in maturity.

In this scenario, winter wheat was projected to flower approximately in the middle of May, while maturing in the middle of July.

Changins:

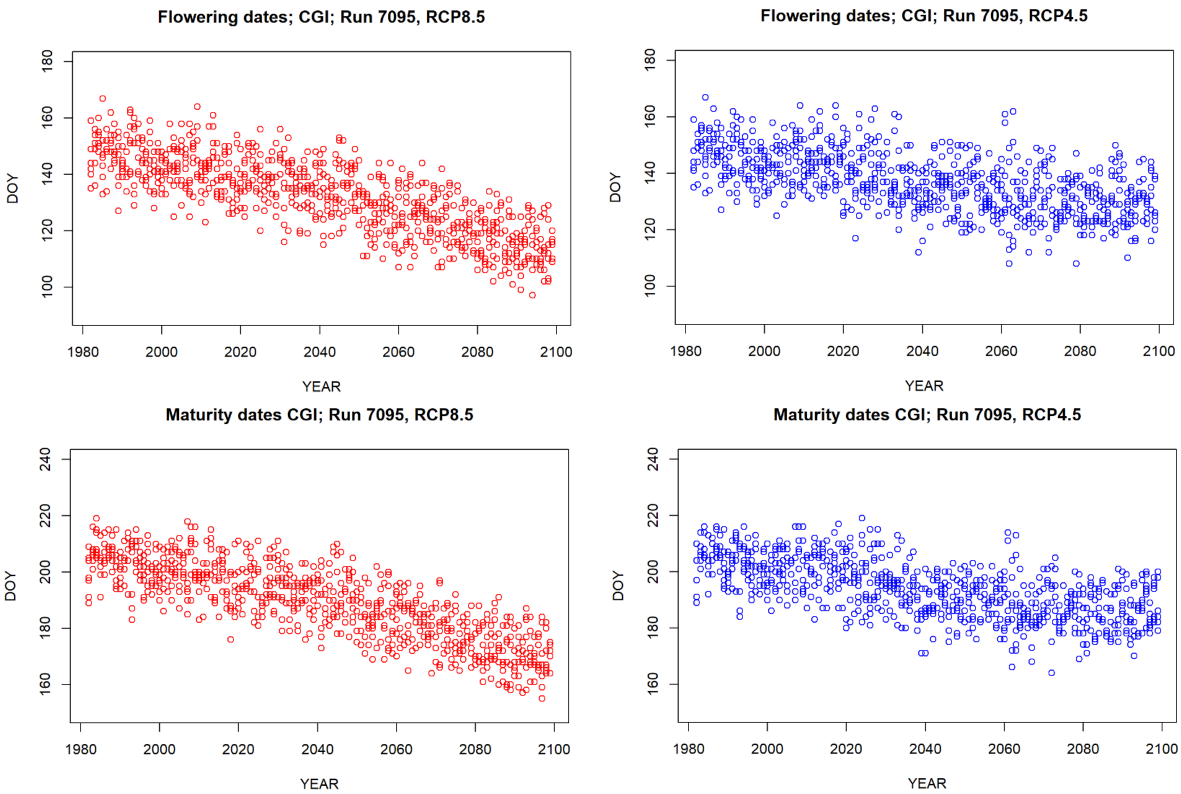


Fig. 17: Flowering and maturity dates shown as day of year. Projections for Changins run number 7095 under different climate change scenarios RCP 8.5 and RCP 4.5. Top left: flowering dates under RCP 8.5 (red), bottom left: maturity dates under RCP 8.5 (red), top right: flowering dates under RCP 4.5 (blue), bottom right: maturity dates under RCP 4.5 (blue)

Projections for winter wheat phenology in Changins showed a similar pattern to Reckenholz. In the high emission scenario, flowering dates were predicted to shift forward by 24.4 days when comparing periods 2020-2029 to 2090-2099, from day 138.8 to day 114.4. The mean maturity dates were predicted to shift by 25.5 days, from day 195.8 in 2020-2029 to day 170.3 in 2090-2099. In Changins, this forward shift of the phenology timings amounted to 3.49 days per decade for flowering, and 3.64 days per decade for the maturity. In this scenario, winter wheat was projected to flower approximately one week earlier than in Reckenholz, but still at the start of May. Similarly, the crop was projected to mature a week earlier than in Reckenholz, at the end of June.

If the world follows the RCP 4.5 emission scenario, these shifts in phenology would also be less pronounced in Changins. In these projections, the mean flowering date was simulated to shift forward by 11.1 days, from day 140.9 in 2020-2029 to day 129.8 in the period 2090-2099. Likewise, the projected mean maturity date was shifted forward by 10.9 days, from day 197.6 in 2020-2029 to day 186.7 in 2090-2099. Quantified in days per decade, RCP 4.5 caused a forward shift of 1.58 days per decade for flowering, and 1.56 days per decade for the maturity of the crop. Compared to the RCP 4.5 scenario for Reckenholz, winter wheat was projected to flower and mature approximately one week earlier in Changins.

4.3.2 Yield Projections

Next, we turned to assessing the projected impact of climate change on winter wheat storage organ production. The following graphs show the yield simulations for winter wheat in the 21st century, with all the GCM-RCM-model chains combined as an ensemble. As seen previously, this was performed for both RCP 8.5 in red and RCP 4.5 in blue. Additionally, the areas in brown (720ppm) and purple (1000ppm) show the winter wheat yield under the influence of high levels of CO2 fertilization. As these high CO2 levels are only reached in RCP 8.5, these areas are only shown for that scenario.

<u>Reckenholz:</u>

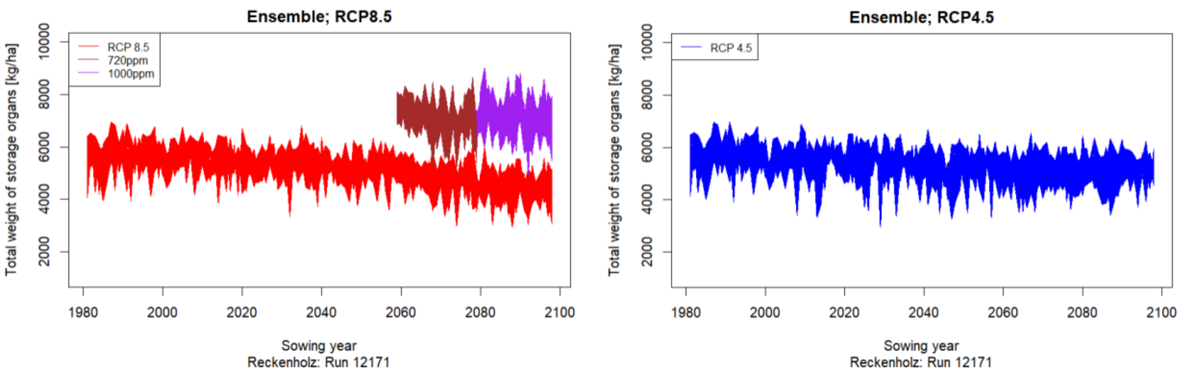


Fig. 18: Annual yield projections for Reckenholz, ensemble. Left: winter wheat yield under RCP 8.5 (red), including CO2 fertilization effect (720ppm shown in brown, 1000ppm shown in purple). Right: winter wheat yield under RCP 4.5 (blue). Run number 12171.

The graphs show a decline in winter wheat yield in Reckenholz as the century progresses in both scenarios. However, this decline was far more pronounced in the RCP 8.5 scenario, reducing the average annual yield from 5391.5 [kg/ha] for the period 2020-2029 to 4425.8 [kg/ha] in 2090-2099. This amounted to a 17.91% decrease in mean yield. As a comparison, winter wheat under RCP 4.5 produced an annual mean yield of 5405.6 [kg/ha] in 2020-2029, declining to 5180.7 [kg/ha] in 2090-2099, which represented a 4.16% decrease in mean yield.

Interestingly, this simulation projected winter wheat crops to benefit greatly when CO2 fertilization is considered. The effect of 720ppm CO2 in the atmosphere was projected to boost the average yield to 7006.33 [kg/ha] for the period 2070-2079, while 1000 ppm was projected to increase mean yield levels to 7054.35 [kg/ha] for 2090 to 2099. In comparison to the average observed yield in Reckenholz (1989-2017) used for the calibration of the WoFoSt model (5575.941 [kg/ha]), this amounted to a 25.65% increase in wheat yield for the 720ppm case, and a 26.51% increase in the 1000ppm case. However, when comparing the CO2 fertilized yields with the non-fertilized yields for the same time periods (2070-2079 and 2090-2099) for RCP 8.5; 720 ppm caused a 47.03% increase in yield, while 1000 ppm caused a 59.39% increase in yield levels.

Changins:

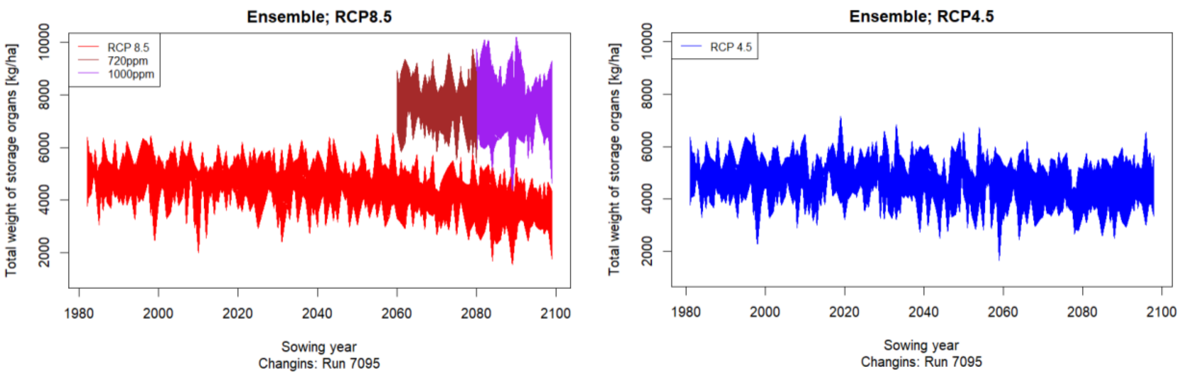


Fig. 19: Annual yield projections for Changins, ensemble. Left: winter wheat yield under RCP 8.5 (red), including CO2 fertilization effect (720ppm shown in brown, 1000ppm shown in purple). Right: winter wheat yield under RCP 4.5 (blue). Run number 7095.

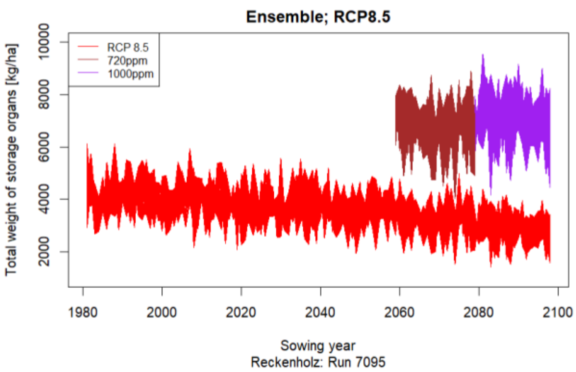
In Changins, winter wheat production declined in the RCP 8.5 scenario, while no clear trend was visible under RCP 4.5. In the case of RCP 8.5, the average annual yield decreased from

4816.2 [kg/ha] in 2020-2029 to 3667.3 [kg/ha] in 2090-2099 (-23.85%). The average annual yield under RCP 4.5 was projected to be 4864.4 [kg/ha] in 2020-2029, which was reduced to 4570.8 [kg/ha] in 2090-2099 (-6.04%). The CO2 fertilization effect was projected to be stronger than in Reckenholz, increasing average yield levels for 2070-2079 to 7606.71 [kg/ha] and to 7672.60 [kg/ha] for the period of 2090-2099. Comparing this to the observed values for yields in Changins (2005-2015: 5330.178 [kg/ha]) yielded an increase of 42.71% for 720ppm, and 43.95% for 1000ppm. When comparing the CO2 fertilized yields to the simulated yields in RCP 8.5 a more drastic increase in comparative yield could be seen: An 88.43% increase in yield for the 2070-2079 period with 720ppm, and a 109.22% increase in yield in the 1000 ppm scenario for 2090-2099.

It was clear to see that the WoFoSt simulation showed the possible advantages of CO2 fertilization under climate change. The effect was far more pronounced in Changins because the base RCP 8.5 yield levels decreased by more in Changins than in Reckenholz, while the introduction of higher CO2 levels caused higher yield increases in Changins.

To ensure that the previous simulations accurately represent the production trends of winter wheat in the respective scenario, we applied the highest index of agreement runs for the other locations to these two locations (run numbers: 7095, 491, 16327 and 8309 in Reckenholz; run numbers 12171, 491, 16327 and 8309 in Changins).

<u>Reckenholz:</u>



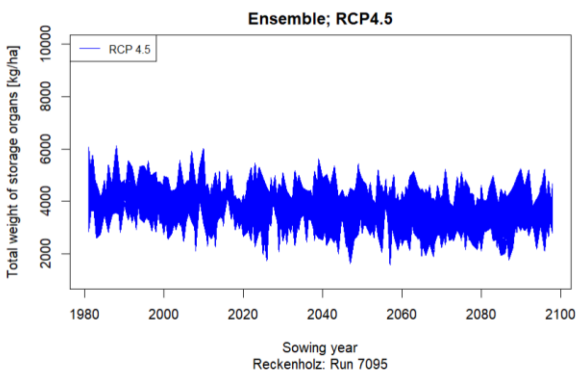


Fig. 20: Annual yield projections for Reckenholz, ensemble. Left: winter wheat yield under RCP 8.5 (red), including CO2 fertilization effect (720ppm shown in brown, 1000ppm shown in purple). Right: winter wheat yield under RCP 4.5 (blue). Run number 7095.

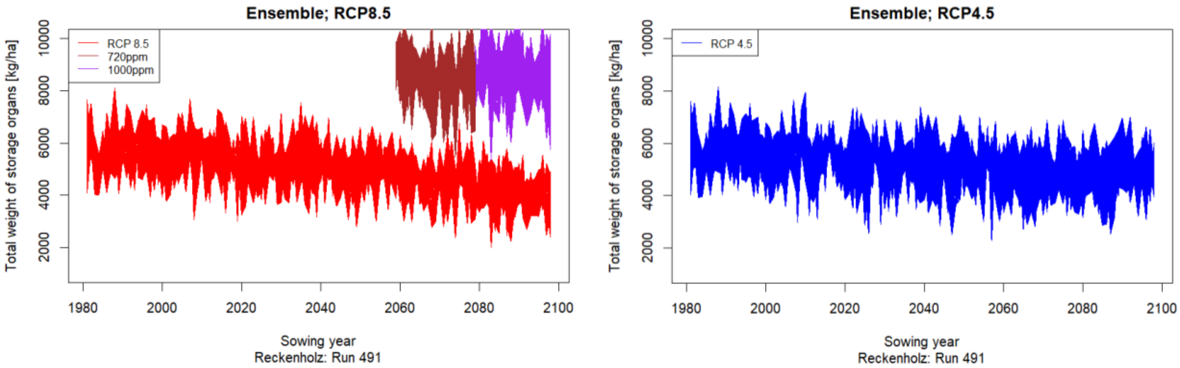


Fig. 21: Annual yield projections for Reckenholz, ensemble. Left: winter wheat yield under RCP 8.5 (red), including the CO2 fertilization effect (720ppm shown in brown, 1000ppm shown in purple). Right: winter wheat yield under RCP 4.5 (blue). Run number 491.

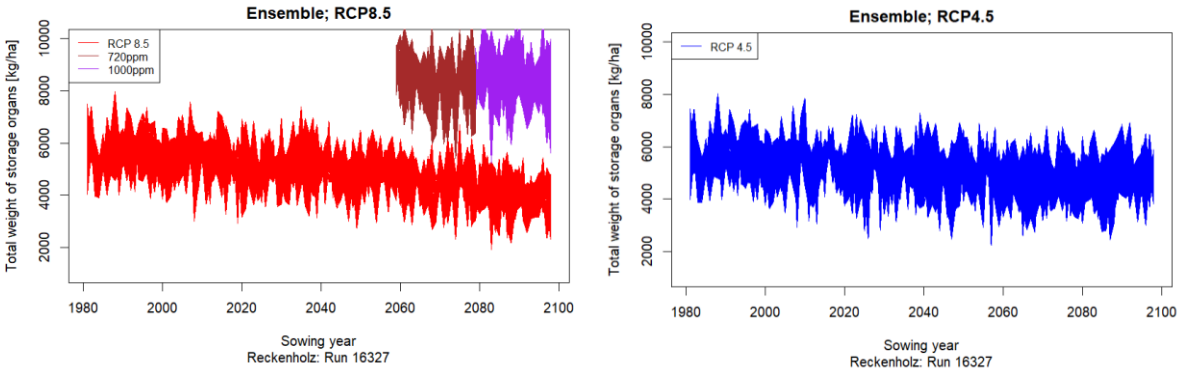


Fig. 22: Annual yield projections for Reckenholz, ensemble. Left: winter wheat yield under RCP 8.5 (red), including the CO2 fertilization effect (720ppm shown in brown, 1000ppm shown in purple). Right: winter wheat yield under RCP 4.5 (blue). Run number 16327.

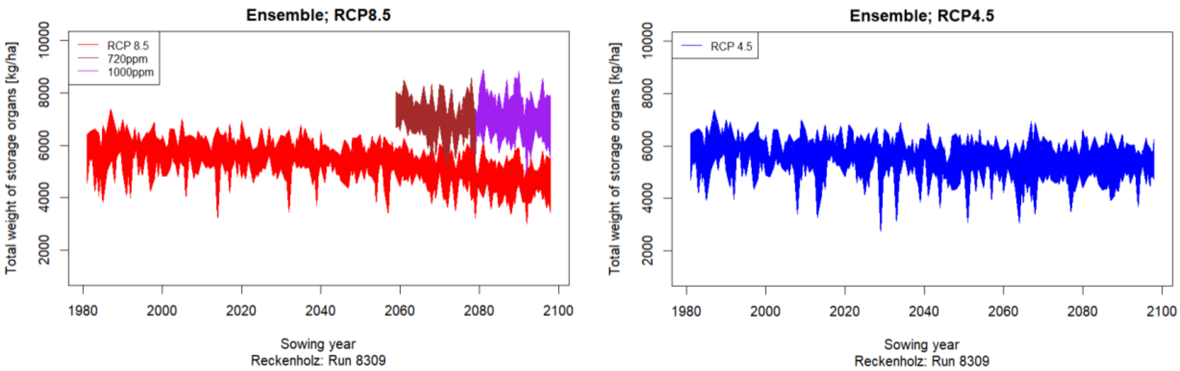


Fig. 23: Annual yield projections for Reckenholz, ensemble. Left: winter wheat yield under RCP 8.5 (red), including the CO2 fertilization effect (720ppm shown in brown, 1000ppm shown in purple). right: winter wheat yield under RCP 4.5 (blue). Run number 8309.

Changins:

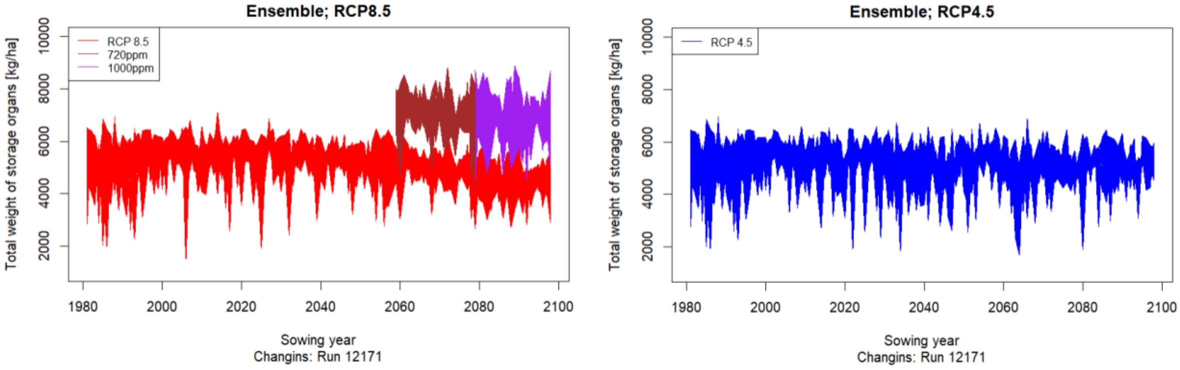


Fig. 24: Annual yield projections for Changins, ensemble. Left: winter wheat yield under RCP 8.5 (red), including the CO2 fertilization effect (720ppm shown in brown, 1000ppm shown in purple). Right: winter wheat yield under RCP 4.5 (blue). Run number 12171.

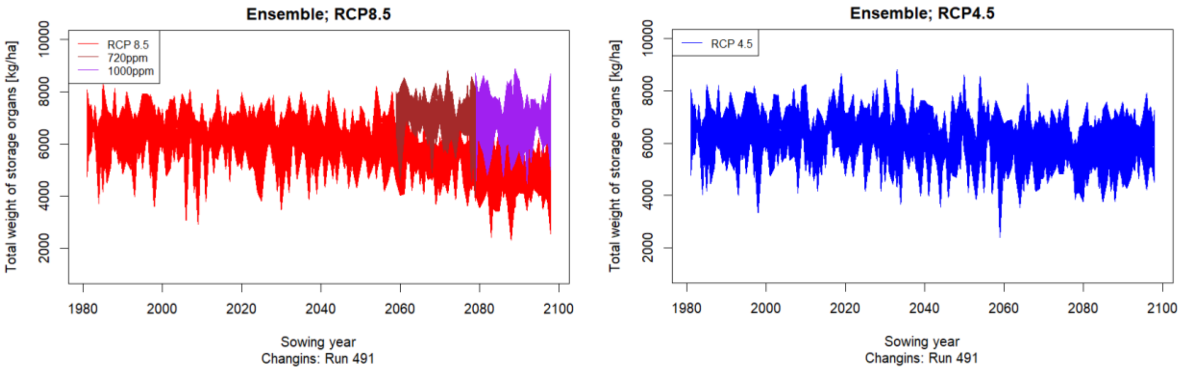


Fig. 25: Annual yield projections for Changins, ensemble. Left: winter wheat yield under RCP 8.5 (red), including the CO2 fertilization effect (720ppm shown in brown, 1000ppm shown in purple). Right: winter wheat yield under RCP 4.5 (blue). Run number 491.

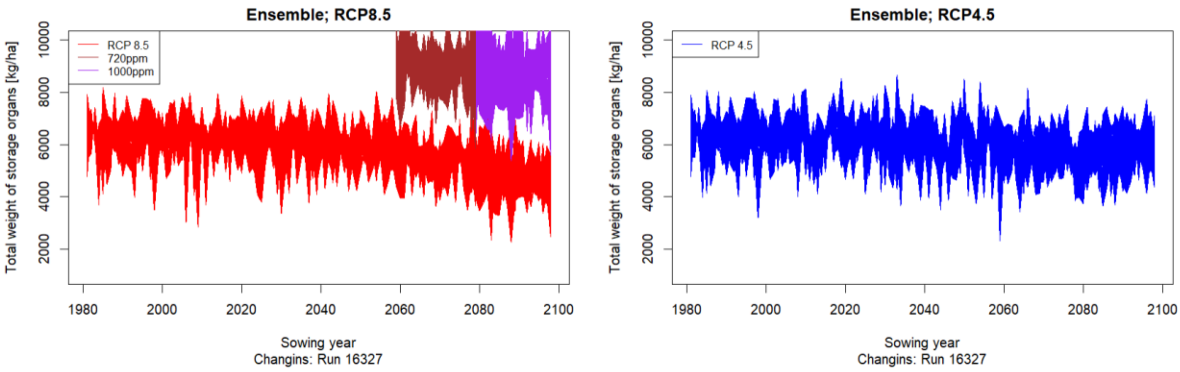


Fig. 26: Annual yield projections for Changins, ensemble. Left: winter wheat yield under RCP 8.5 (red), including the CO2 fertilization effect (720ppm shown in brown, 1000ppm shown in purple). Right: winter wheat yield under RCP 4.5 (blue). Run number 16327.

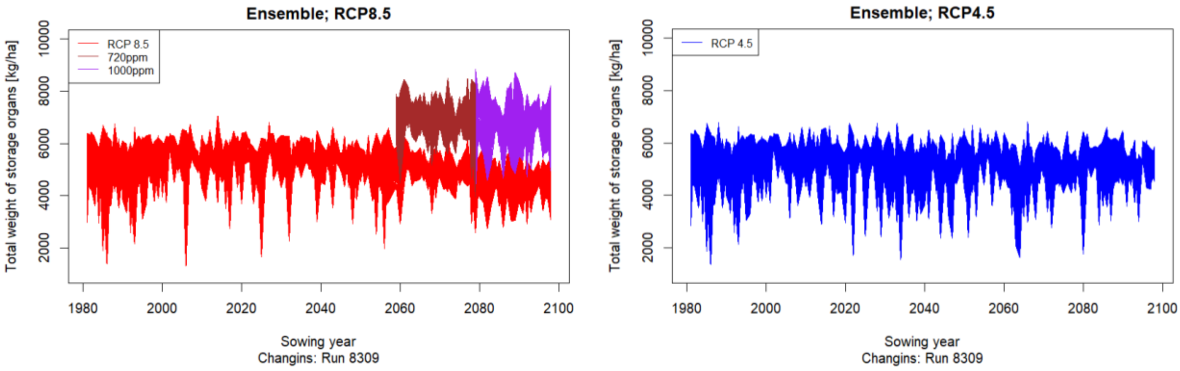


Fig. 27: Annual yield projections for Changins, ensemble. Left: winter wheat yield under RCP 8.5 (red), including the CO2 fertilization effect (720ppm shown in brown, 1000ppm shown in purple). Right: winter wheat yield under RCP 4.5 (blue). Run number 8309.

For both Reckenholz and Changins, figures 20-27 show that the projection runs based on the calibration of other locations yielded similar results: larger yield declines in the higher emission scenario than the low emission scenario, while the CO2 fertilization significantly boosted the productivity level of the crop. Production levels did vary for both RCP scenarios, as did the impact that increased levels of atmospheric CO2 concentration had on yield in the higher emission scenario.

4.3.3 Drought stress projections

Finally, WoFoSt produced information on the drought stress that winter wheat crops suffered from during cultivation. This information was given daily in binary form, with 0 being a day without drought stress and 1 indicating a day that exhibited symptoms of drought stress. This drought stress analysis was performed on the projection ensembles of Reckenholz and Changins, for their respective highest performing simulations 12171 and 7095. Moreover, the analysis incorporated the effects of the five different soil types mentioned previously: EC3, Grafenried 1, Grafenried 2, Reckenholz 1, and Reckenholz 2.

Reckenholz:

The following graphs show the mean projected annual drought stress days for Reckenholz across all seven GCM-RCM-model chains.

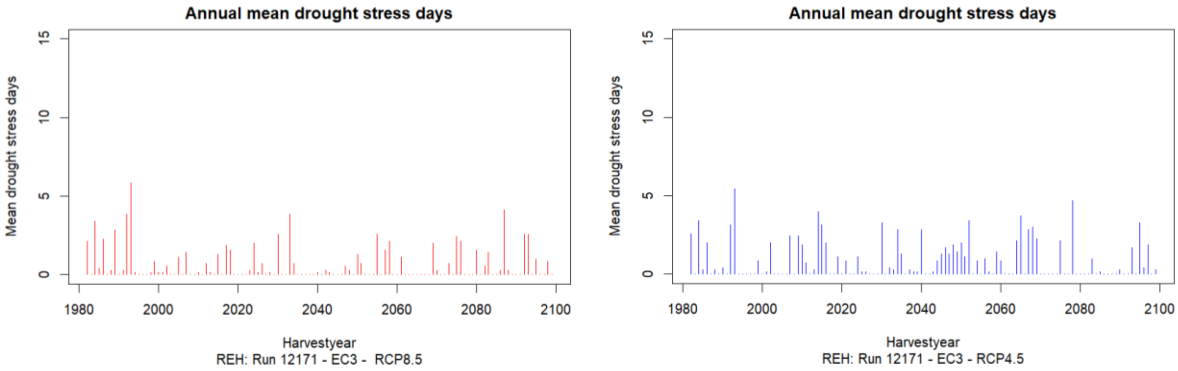


Fig. 28: Annual mean drought stress days; Reckenholz projection data; run 12171; EC3 soil. Left: Mean drought stress days under RCP 8.5. Right: Mean drought stress days under RCP 4.5.

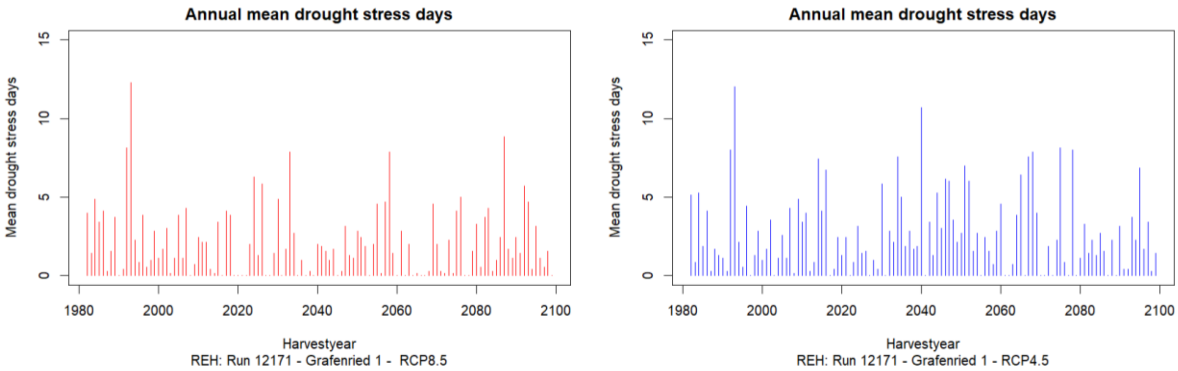


Fig. 29: Annual mean drought stress days; Reckenholz projection data; run 12171; Grafenried 1 soil. Left: Mean drought stress days under RCP 8.5. Right: Mean drought stress days under RCP 4.5.

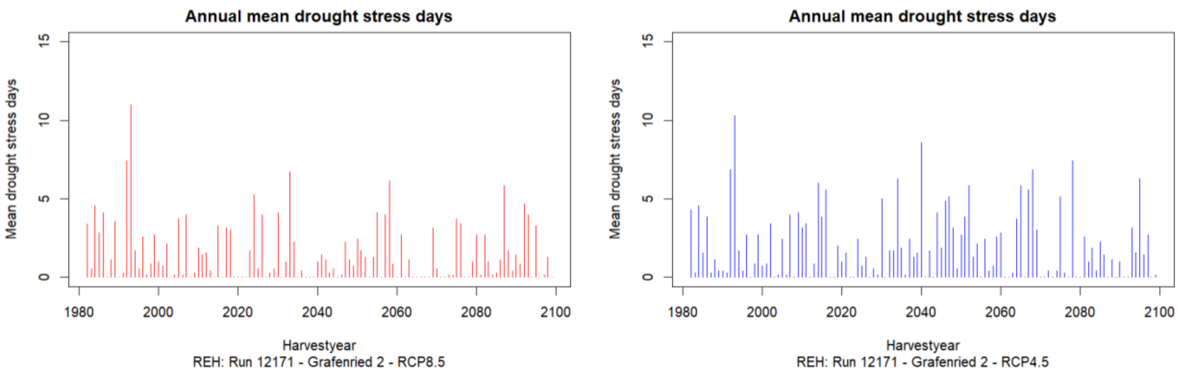


Fig. 30: Annual mean drought stress days; Reckenholz projection data; run 12171; Grafenried 2 soil. Left: Mean drought stress days under RCP 8.5. Right: Mean drought stress days under RCP 4.5.

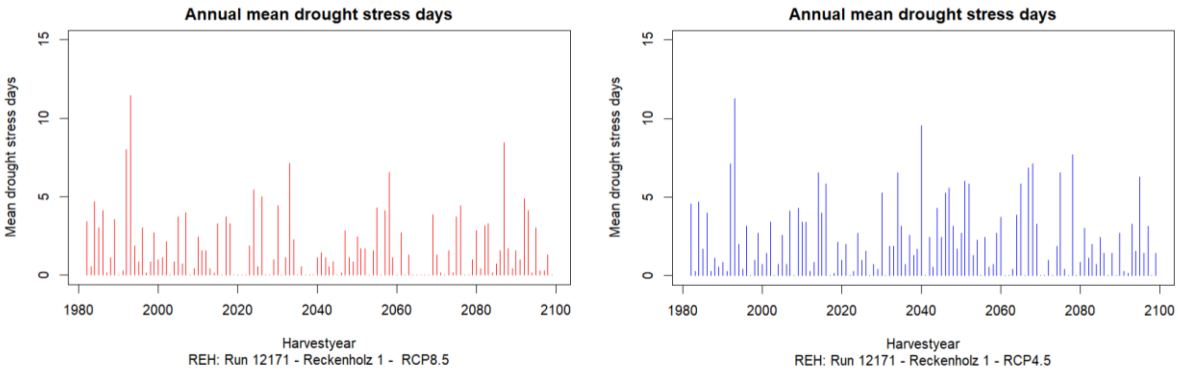


Fig. 31: Annual mean drought stress days; Reckenholz projection data; run 12171; Reckenholz 1 soil. Left: Mean drought stress days under RCP 8.5. Right: Mean drought stress days under RCP 4.5.

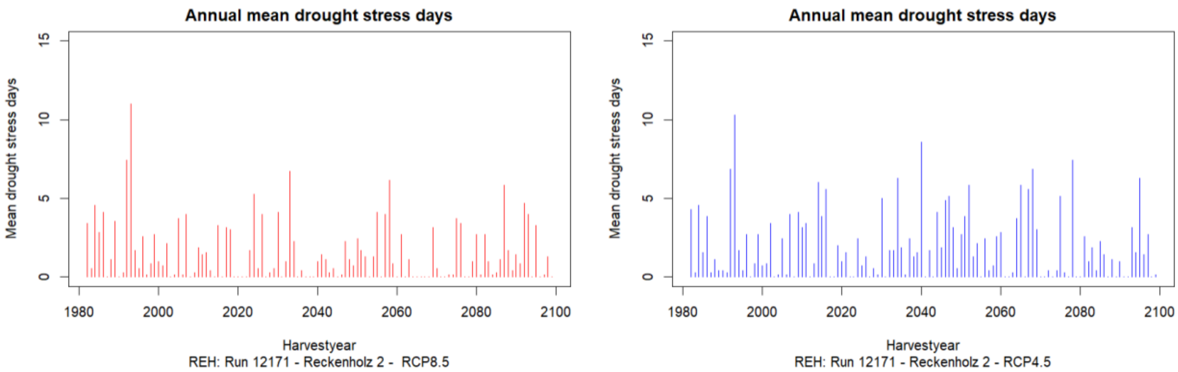


Fig. 32: Annual mean drought stress days; Reckenholz projection data; run 12171; Reckenholz 2 soil. Left: Mean drought stress days under RCP 8.5. Right: Mean drought stress days under RCP 4.5.

Mann-Kendall tests were performed to look for trends in the drought stress findings and no significant trends were found. While the graphs paint a picture of the mean annual drought stress days, the following table describes the number of mean drought stress days for these projections in the near future (2022-2050) and the far future (2070-2099).

Table 9: Reckenholz projection run number 12171 mean drought stress days for the near (2022-2050) and far future (2070-2099) under RCP 8.5 (red) and RCP4.5 (blue) using different soil files: EC3, Grafenried 1, Grafenried 2, Reckenholz 1, Reckenholz 2.

Reckenholz	EC3	Grafenried 1	Grafenried 2	Reckenholz 1	Reckenholz 2
2022-2050 RCP 8.5	0.48	1.86	1.35	1.49	1.35
2022-2050 RCP 4.5	0.87	3.10	2.22	2.56	2.22
2070-2099 RCP 8.5	0.70	2.13	1.36	1.72	1.36
2070-2099 RCP 4.5	0.53	2.03	1.36	1.70	1.36

The projections with all five different soil files showed a clear indication of increased drought stress under RCP 4.5 in the near future, compared to RCP 8.5 projections in Reckenholz. Table 9 illustrates this. However, under RCP 4.5 the drought stress decreased in the far future, contrary to the effect RCP8.5 had on drought stress, where the number of mean drought stress days increased slightly as the century progressed.

The WoFoSt soil file EC3 exhibited far less drought stress than the other soil profiles, under both RCP 4.5 and RCP 8.5, only exceeding five mean drought stress days once. The mean annual drought stress days of the four soil profiles from Grafenried and Reckenholz developed very similarly in Reckenholz. Table 9 reveals that the Grafenried 1 soil profile caused the crop to suffer the highest amount of drought stress, followed by the Reckenholz 1 soil profile. Grafenried 2 and Reckenholz 2 were almost identical in the drought analysis, revealing no difference in the mean number of drought stress days in the near and far future.

In order to analyse the drought stress of winter wheat projections under RCP 8.5, we took the CO_2 fertilization into account, and compared the same periods (2060-2080, 2080-2099) as in the yield analysis. The following table highlights the differences in Reckenholz with and without CO_2 fertilization taken into account:

Table 10: Mean drought stress days for the periods 2060-2080 (720ppm) and 2080-2099 (1000ppm) with and without CO2 fertilization under RCP8.5, using different soil files: EC3, Grafenried 1, Grafenried 2, Reckenholz 1, Reckenholz 2 on Reckenholz projection run number 12171:

Reckenholz	**EC3**	**Grafenried 1**	**Grafenried 2**	**Reckenholz 1**	**Reckenholz 2**
2060-2080	0.49	1.37	0.89	1.10	0.89
2060-2080 (+CO2,720ppm)	0.40	1.11	0.76	0.90	0.76
2080-2099	0.76	2.42	1.59	1.96	1.59
2080-2099 (+CO2,1000 ppm)	0.59	2.03	1.34	1.67	1.34

CO2 fertilization of both 720ppm and 1000ppm caused reductions in mean drought stress occurrence at the location Reckenholz for every Soil profile for the given time periods. The reduction was larger with higher levels of CO2 fertilization. Using the Grafenried 1 soil caused the highest reductions in drought stress in this case, with reductions of 0.26 mean days in the 720ppm scenario and 0.39 mean drought stress days in the 1000ppm scenario. The Reckenholz 1 profile saw the second highest decrease (0.2 and 0.29 days), followed by Grafenried and Reckenholz 2 (0.13 and 0.25 days), while the smallest decrease of drought stress was measured for the EC3 soil profile, which showed decreases of 0.9 and 0.17 mean drought stress days.

Changins:

As before, the following graphs show the mean projected annual drought stress days for Changins across all seven GCM-RCM-model chains.

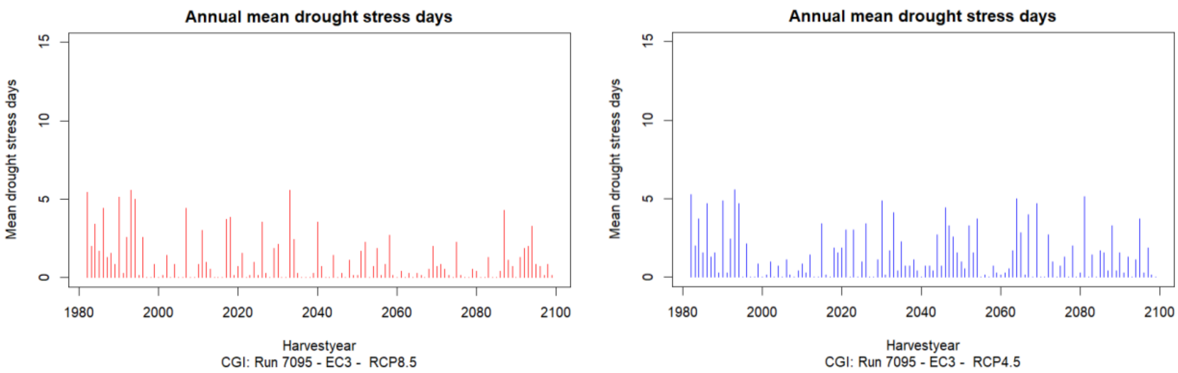


Fig. 33: Annual mean drought stress days; Changins projection data; run 7095; EC3 soil. Left: Mean drought stress days under RCP 8.5. Right: Mean drought stress days under RCP 4.5.

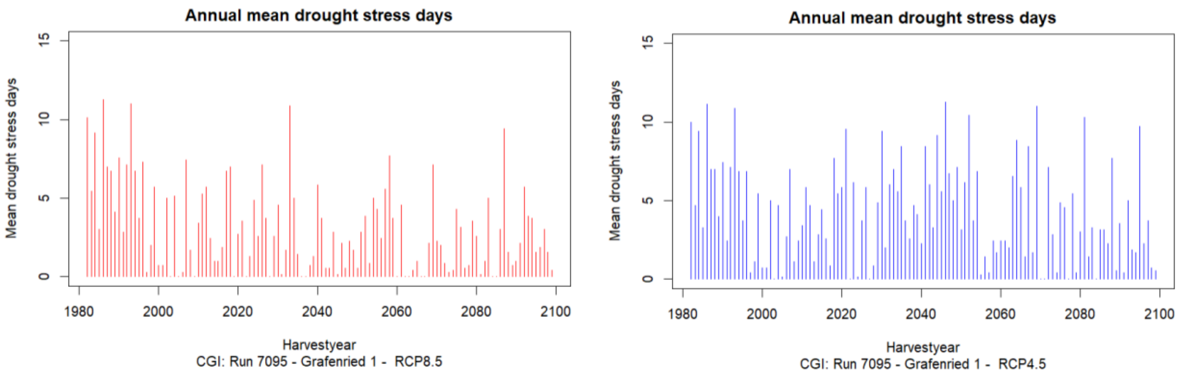


Fig. 34: Annual mean drought stress days; Changins projection data; run 7095; Grafenried 1 soil. Left: Mean drought stress days under RCP 8.5. Right: Mean drought stress days under RCP 4.5.

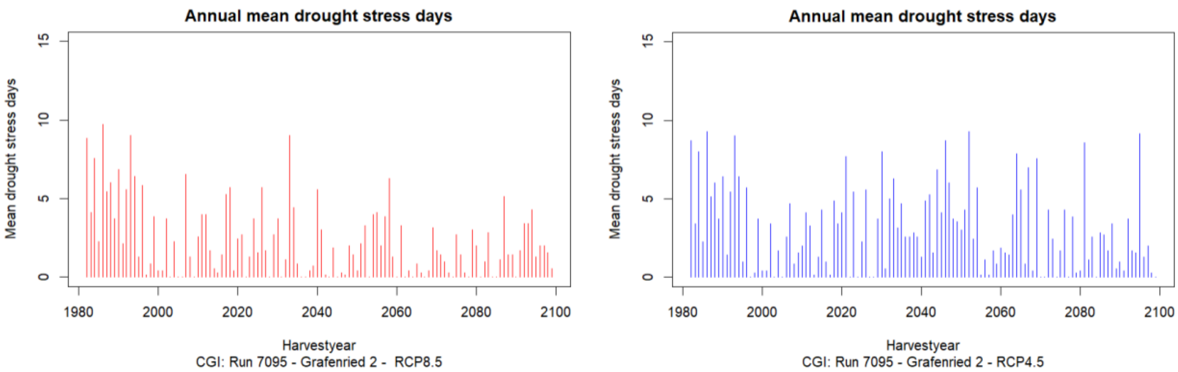


Fig. 35: Annual mean drought stress days; Changins projection data; run 7095; Grafenried 2 soil. Left: Mean drought stress days under RCP 8.5. Right: Mean drought stress days under RCP 4.5.

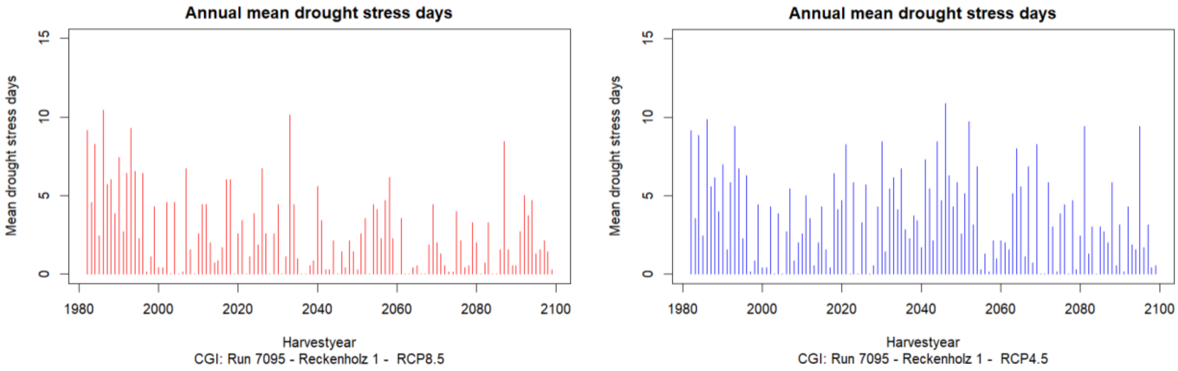


Fig. 36: Annual mean drought stress days; Changins projection data; run 7095; Reckenholz 1 soil. Left: Mean drought stress days under RCP 8.5. Right: Mean drought stress days under RCP 4.5.

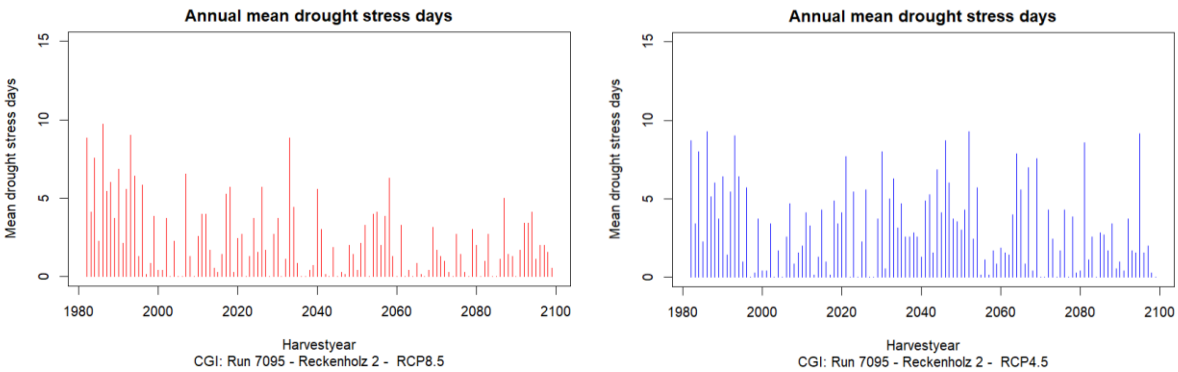


Fig. 37: Annual mean drought stress days; Changins projection data; run 7095; Reckenholz 2 soil. Left: Mean drought stress days under RCP 8.5. Right: Mean drought stress days under RCP 4.5.

As before, Mann-Kendall tests were performed to look for trends in the drought stress findings and no significant trend was found. The drought stress data for the near and far future is captured in the following table:

Table 11: Changins projection run number 7095 mean drought stress days for the near (2022-2050) and far future (2070-2099) under RCP 8.5 (red) and RCP4.5 (blue) using different soil files: EC3, Grafenried 1, Grafenried 2, Reckenholz 1, Reckenholz 2.

Changins	EC3	Grafenried 1	Grafenried 2	Reckenholz 1	Reckenholz 2
2022-2050 RCP 8.5	0.93	2.50	1.87	2.13	1.87
2022-2050 RCP 4.5	1.49	5.07	3.66	4.37	3.66
2070-2099 RCP 8.5	0.82	2.21	1.57	1.87	1.54
2070-2099 RCP 4.5	1.08	3.0	2.07	2.63	2.08

Comparing RCP 4.5 projections in the near and far future showed that the number of mean drought stress days decreased for every soil file in the low emission scenario. Contrary to the findings in Reckenholz for RCP 8.5, our projection data for Changins indicated a decrease in the number of mean drought stress days for all soil files in the high emission scenario. Moreover, the projections for Changins in the far future indicate higher drought stress under RCP 4.5 than under RCP 8.5. Overall, the level of drought stress was higher in Changins than in Reckenholz. As before, the EC3 soil drought projection was far lower than the rest, while Grafenried 2 and Reckenholz 2 delivered almost identical results.

To analyse the impact of higher levels of ambient CO2 in the atmosphere on the number of mean drought stress days in Changins, the next table shows the effect that CO2 concentration levels of 720 ppm, as well as 1000 ppm have on the drought stress projections.

Table 12: Mean drought stress days for the periods 2060-2080 (720ppm) and 2080-2099 (1000ppm) with and without CO2 fertilization under RCP8.5, using different soil files: EC3, Grafenried 1, Grafenried 2, Reckenholz 1, Reckenholz 2 on Changins projection run number 7095:

Changins	EC3	Grafenried 1	Grafenried 2	Reckenholz 1	Reckenholz 2
2060-2080	0.45	1.71	1.06	1.30	1.05
2060-2080 (+CO2,720ppm)	1.41	3.09	1.91	2.50	1.90
2080-2099	0.97	2.41	1.76	2.08	1.72
2080-2099 (+CO2,1000ppm)	1.61	4.34	3.19	3.9	3.17

When taking CO2 fertilization into account in the Changins projections, further differences between the two locations became clear. As opposed to the Reckenholz projections, the drought stress increased in Changins with all five soil files, because of increased levels of CO2 in the atmosphere. The largest increase can be seen for the Grafenried 1 soil profile, where the mean number of drought stress days increased by 1.38 days for 720ppm and 1.93 days for 1000ppm. Grafenried 2 saw the second largest increase in drought stress days under 720ppm and 1000ppm: 1.2 days and 1.82 days, respectively. Grafenried 2 exhibited increases of 0.85 (720ppm) and 1.43 days (1000ppm), Reckenholz 2 showed similar results (0.85 and 1.45 days, respectively). Finally, the EC3 soil profile showed increased numbers of drought stress days as well: 0.96 days for the 720ppm scenario and 0.64 under the 1000ppm scenario.

5.Discussion

5.1 Phenology changes under climate change

In this study, different climate change scenarios were modelled to affect winter wheat phenology. When average data from the years 2090-2099 were compared to data from the years 2020-2029 under the RCP 4.5 scenario, heading dates were projected to advance by 9.8 days in Reckenholz (1.4 days per decade) and 11.1 days in Changins (1.58 days per decade). In the higher emission scenario RCP 8.5, this shift was more pronounced: The flowering dates in Reckenholz advanced by 22.2 days on average (3.17 days per decade), and by 24.4 days in Changins (3.49 days per decade). Similarly, the projected maturity dates shifted by 10.5 days in Reckenholz (1.5 days per decade) and 10.9 days in Changins (1.56 days per decade) under RCP 4.5. RCP 8.5 caused a larger forward shift in projected maturity dates: 24.4 days in Reckenholz (2.11 days per decade), and 25.5 days in Changins (3.64 days per decade). These projected shifts are slightly larger than the predictions of Gouache et al. (2012) and Rogger et al (2021). Gouache et al. (2012) projected winter wheat to flower two to three weeks earlier by the end of the 21st century at 10 sites in France. The flowering shift in days per decade that is found in our study is higher in both locations as in Rogger et al. (2021) who founnd an average heading date advancement on wheat in Switzerland of 2.6 days per decade. As highlighted by Rogger et al. (2021), this phenological earliness comes at the cost of reduced yield levels and is considered a cause of reduced grain yields. More specifically, the shorter maturation phase gives the crop less time to intercept radiation to produce biomass (Semenov & Shewry, 2011; Holzkämper et al., 2014). As seen above, this study supports these findings. Under RCP 4.5, the phenological shift was less pronounced than under RCP 8.5 and the yield levels dropped by less in the lower emission scenario. Under RCP 8.5, yield reductions of -17.91% and -23.85% could be seen for Reckenholz and Changins respectively, while RCP 4.5 caused a less pronounced reduction at both sites, namely -4.16% and -6.04%. While the phenological shifts impact the average yield levels, it is not possible to pinpoint yield reductions to be due to changes in phenology alone. Other factors such as heat, frost, and drought stress, as well as pests and diseases, can impact future yield levels. However, changes in phenology can affect the impact these stress factors have on crop growth.

5.2 Impact of Phenological Shifts and CO2 Fertilization on Heat and Drought Stress

Phenological earliness shifts critical growing periods like flowering and grain filling forward, away from potential heat (Rogger et al., 2021; Mäkinen et al., 2018) and drought stress periods (Semenov & Shewry, 2011; Holzkämper et al., 2014; Mäkinen et al., 2018: Gouache et al., 2012). Different estimates on the impact of stress factors for winter wheat exist in the literature. Semenov & Shewry (2011) found that for winter wheat grown in Europe in 2055 under a scenario where CO2 concentration levels reach 338 ppm, relative yield losses from drought stress will decrease. They showed the most limiting factor for future winter wheat growth to be heat stress. Their research suggests that heat stress during anthesis reduced grain number, while heat stress five days thereafter reduced grain size. Research by Webber et al. (2018) on the drought stress response of winter wheat in Europe under climate change in the years 2040 to 2069 with ambient CO2 levels of 360 ppm did not find increased levels of average heat and drought stress for wheat in Europe on average. They did find different patterns within Europe. In their study, Webber et al. (2018) projected increasing drought stress in eastern Europe, while projections for France and southern Europe exhibited lower levels of drought stress. These results were slightly different when only taking low yield years into account, where wheat growth in Europe incurred an average reduction in yield of 5% because of drought stress. They also took higher levels of atmospheric CO2 levels into account: 442ppm, 499ppm as well as 571ppm for RCPs 2.6, 4.5 and 8.5, respectively. CO2 fertilization reduced average yield losses because of drought for wheat, particularly in regions where drought was not considered a strong yield limitation. However, their study shows that the CO2 fertilization was not able to alleviate drought stress losses in low yielding years. Mäkinen et al. (2018) analysed the impact of agro-climatic extremes on the yield of 991 different wheat cultivars, compared to normal conditions. They found that, under extreme heat, 77% of cultivars experienced yield reductions. For drought, they split their findings into extreme drought events from sowing to heading, and drought events between heading and maturity of the crop. In the case of drought events from sowing to heading, 51% of the studied cultivars showed yield increases, and the remaining 49% showed reductions in yield levels. Whereas many wheat cultivars performed well as a response to drought events between heading and maturity, with only one cultivar showing yield decreases of 10% because of drought in this period.

As this study focused on winter wheat growth in Switzerland, studies performed on wheat growth in Switzerland (Holzkämper et al., 2014; Rogger et al., 2021), paint a more relevant picture to compare this study’s findings to. In their research on regional trends in climate suitability of winter wheat in Switzerland for the period 1983 to 2010, Holzkämper et al. (2014) found the most limiting factors of winter wheat cultivation to be excess water, as well as frost and heat stress. While water stress as limitation was not considered to be very restricting for winter wheat cultivation, their study did find that winter wheat grown on the

Swiss central plateau as well as the inner alpine valleys in the south of the country exhibited water limitations to some degree. Research by Rogger et al. (2021), focused on the future heat stress exposure of different winter wheat varieties grown at four sites on the Swiss central plateau. Their study used the same climate projection data CH2018 (CH2018, 2018) as our study. They found increased heat stress exposure of winter wheat in Switzerland between 2075 and 2099, in comparison to 1982 to 2006, for both RCP 2.6 and RCP 8.5. Their findings indicate higher levels of heat stress on winter wheat, despite phenological escape.

This study finds that phenological earliness causes reductions in drought stress in Changins under both RCP scenarios, while a reduction in mean drought stress days can only be seen in RCP 4.5 for Reckenholz. Under RCP 8.5, the phenological escape does not suffice to reduce the mean drought stress in the Reckenholz projection for all soil types. While RCP 4.5 causes greater drought stress than RCP 8.5 in the near future for both locations, the drought stress in the far future of the lower emission scenario RCP 4.5 is higher than RCP 8.5 in Changins but slightly lower than the high emission scenario in Reckenholz. The comparison of the number of drought stress days in the far future indicates that the phenological drought escape is more pronounced in Changins. This can be caused by multiple factors: different climatic conditions in the locations, different parametrization of the two projection runs 12171 and 7095, as well as the more pronounced phenological shift in Changins are likely causes of this difference in drought stress response to climate change.

When considering the additional impact of increased CO2 levels in the high emission scenario, we also see different developments in Reckenholz and Changins. Both locations show increased numbers of mean drought stress days in 2080-2099 without comparing CO2 fertilized and non-CO2 fertilized projections. However, when cross analysing CO2 fertilized, and non-CO2 fertilized scenarios a different conclusion emerges for the two locations. In Reckenholz, the mean drought stress days under CO2 fertilized projections for both timeframes are lower than the drought stress in the case of the respective projection timeframe without CO2 fertilization for all soil parametrizations. This indicates the potential for reductions in yield losses due to drought stress as a result of higher CO2 levels, as found in Webber et al. (2018). In Changins however, the CO2 fertilized projections exhibited higher levels of mean drought stress days than the projections without this effect. A possible explanation for this increase in drought stress with increased levels of atmospheric CO2 concentration can be found in the research of Webber et al. (2018) as well. They point out that the increased levels of LAI as a response to the CO2 fertilization could result in higher water demand of the crop. We speculate that this effect is only visible in Changins as all soil types studied show higher levels of mean drought stress than in Reckenholz.

5.3 Effect of CO2 Fertilization on Yield and Grain Quality

While winter wheat storage organ production is modelled to decrease in higher RCP scenarios in our findings, this study also shows relevant increases in yield potential when CO2 fertilization is considered. For both Reckenholz and Changins, the fertilization more than offsets the yield reduction in RCP 8.5. The yield level with CO2 fertilization exceeds the observed yield between 1989 and 2017 by 25.65% (720 ppm) and 26.51% (1000 ppm) for Reckenholz. In Changins, the effect is more pronounced, increasing yield levels by 42.71% (720 ppm) and 43.95% (1000 ppm) when compared to the observations from 2005-2015. These results clearly show diminishing yield returns for higher CO2 levels. The result for Reckenholz is in line with the findings of the meta-analysis of 59 papers by Wang et al. (2013). They find wheat grain yield to increase by 24% on average across all papers they studied because of increased CO2 levels (450-800 ppm). A difference in the impact of CO2 on yield was found to be the exposure method, where smaller increases (+14%) in yield were found in experiments that performed CO2 fertilization in the form of free air CO2 enrichment (FACE). Due to this they find that studies that do not utilize the FACE method tend to overestimate the yield response to increased levels of ambient CO2. Their study finds the mechanism behind the increased yield potential under CO2 fertilization to be increased levels of photosynthesis in the crop (+33%). However, no change in the harvest index was found, as total above ground biomass production increased by the same amount as grain yield. This resulted in increased LAI levels by an average of 10%. However, they find that the increase in biomass was not matched by increased levels of nitrogen acquisition and assimilation, leading to a dilution of shoot nitrogen concentration.

Studies have been conducted on the quality of wheat yields under climate change, specifically in regard to the quality of the grain for human consumption. In their FACE study, Högy et al.

(2009) examined the impact of increased CO2 levels on winter wheat grain yield and quality, based on three-year observations from 2004 to 2006. They found increased levels of yield (+10.4%) and above ground biomass production (+11.8%), but similarly to Webber et al. (2018), they found no increase in the harvest index of the crop. Significant reductions in grain protein content (-7.4%) were found. Other changes to grain content were: decreases in essential and non-essential amino acids, as well as manganese, iron, cadmium, and silicon. Increases in potassium, molybdenum, lead, and fructose were discovered, as were increases in the amounts of fructose, fructan, lipids, and non-structural carbohydrates per unit area. Furthermore, they reported significant changes to grain size distribution of the yield. These were reductions in yield levels of the largest grain size Type I (>2.8 mm) by 13%, as well as increases in the percentage of the second smallest grain size type III (2.2-2.5 mm) by 27%. They also found increased amounts of grain size types II and IV, which did not show significant impacts of higher CO2 levels.

Our findings and the existing literature have shown that understanding the response of wheat to changing climate factors is a critical component of ensuring food safety in the future. More studies with longer timeframes are necessary to continue to improve our understanding of the various impacts that climate change can have on food crops. This is particularly true for winter wheat, for which Gouache et al. (2012) found that the interaction between CO2 fertilization and increased temperatures remains the source of the largest uncertainty regarding future yield levels.

5.4 Model Evaluation and Uncertainty in Crop Modelling

Overall, WoFoSt proved to be useful and suitable for simulating winter wheat. The addition of photoperiod as suggested in Holzkämper et al. (2014) for winter crops proved to be beneficial to the accuracy of our phenology simulation. As a result, the model shows the most accurate results with regards to phenology, exhibiting a goodness of fit of 0.92 for the timing of heading as well as maturity. The root mean squared error was reasonable for both phenology timings, with a RMSE of 3.73 days for flowering and 3.43 days for crop maturity. This is in line with the accuracy of phenology simulations found in similar studies on winter wheat growth for other locations using WoFoSt. Song et al. (2006) successfully calibrated the phenology simulation of WoFoSt for winter wheat in China, yielding an RMSE of 2.19 days for flowering and a RMSE of 2.1 days for crop maturity. Another example of WoFoSt phenology calibration for winter wheat can be found in the research of Shekhar et al. (2008) for Hisar in the northwest of India. Across three growing periods they modelled the maturity with perfect accuracy, exhibiting a RMSE of 0. However, their heading dates showed a higher RMSE value than our study (=8.9 days). Overall, the phenology simulation of WoFoSt proves to have high potential for projections of crop phenology.

Looking at other aspects of our model evaluation, WoFoSt accurately simulates the LAI development when compared to the lysimeters in Reckenholz with index of agreement values ranging from d=0.79 to d=0.88. The Soil water content was similarly accurate, with maximum d values between 0.76 and 0.83. Our results showed differences between soil types Grafenried- and Reckenholz 1 compared to Grafenried- and Reckenholz 2, with regards to the accuracy of the soil water content simulation. Grafenried- and Reckenholz 1 outperformed the other two soil files in lysimeters 5 and 10, while lysimeter 11 showed very little difference between the respective Reckenholz 1 and Reckenholz 2 soil files (d=0.66; d=0.67). For both the LAI and the SWC simulations, differences in the management of the lysimeters could have an impact on the index of agreement values, as each of the lysimeters show differences in vegetation, planting density, fertilization, and soil type. Moreover, we have shown that the method of soil file aggregation and parametrization had an impact on drought stress projections. In the future we will discuss the impact that different management methods as well as different parametrization options have on simulation accuracy with regards to crop yield and drought stress.

With regards to the yield simulations, WoFoSt did achieve sufficient accuracy, but it had difficulties with the transferability to and from Changins. While the simulation for Changins itself was accurate with an index of agreement of 0.76, the other simulations failed to show a positive interaction with the climatic data from Changins. This is most surprising for Neuchatel, which should show somewhat similar results to Changins due to its geographical proximity. However, the Neuchatel simulation when applied to Changins only showed an agreement index of 0.36, while the Changins simulation applied to Neuchatel was similar, with a value of 0.35. This unsuitability is potentially troubling, as Changins is well known for winter wheat experiments and field studies in Switzerland. The findings of this study could indicate that Changins may not be representative of the rest of Switzerland because of different climatic conditions. Possible explanations for this are the shorter timeframe of yield observations from Changins compared to the other locations, as well as outliers in the observed timeframe, which lead to changes in the development of the yield observations in that timeframe. Consequently, our calibration provided different parametrizations of the crop file for Changins and the other locations. Further studies are required to confirm the differences we find between these locations, ideally using a larger timeframe.

While the projections of winter wheat yield under RCP 8.5 and RCP 4.5 in this study showed similar trends as in other research, multiple sources of uncertainty must be considered. WoFoSt simulations, just like all crop growth simulations, are subject to these various uncertainties. One of the limitations of this study can be found in the uncertainty within the GCM-RCM model chains. Climate predictions are heavily dependent on the representative concentration pathway the world will follow. Any predictions regarding the future climate have an innate amount of variability and inaccuracy. Particularly because climate change will cause more frequent and more intense extreme weather events (IPCC, 2019), which are particularly hard to predict and capture in crop growth modelling. Moreover, when using this data, it can be difficult to pinpoint whether changes in yield levels are a result of changes in precipitation or temperature (Ludwig & Asseng 2010). Another pitfall of crop growth modelling is the inability to model pests and diseases. Not only for the current year, but also for the various climate change scenarios. New pests and diseases could arise in a changing climate, with uncertain effects on the growth of winter wheat and other crops (IPCC, 2019). Finally, the phenological data used for the calibration of WoFoSt was taken only from Changins. While the phenology of winter wheat in Switzerland is likely to be similar, we have shown that small differences in the timing of flowering and grain filling could heavily impact the crop's response to increased temperatures, elevated CO2 levels, and changes in precipitation patterns. Moreover, this study used data from only one winter wheat variety: *Arina*. Location specific phenology data for different winter wheat varieties is likely to yield more accurate results and could provide more insight into the response to climatic change in the 21st century.

6. Conclusion

In this study, it was found that the effects of climate change predictions on winter wheat growth will significantly impact yield levels in Switzerland in the 21st century. In both Reckenholz and Changins, the effect of the high emission scenario RCP 8.5 caused reductions in yield levels (REH: -17.91%; CGI: -23.85%) if CO2 fertilization of the crop is not considered. In contrast to the high emission scenario, the simulations for RCP 4.5 show significantly lower reductions in yield levels (REH: -4.16%; CGI: -6.04%). With the inclusion of high levels of CO2 fertilization (720ppm and 1000ppm), the yield levels increased in both locations, more so in Changins (REH: +25.65% and 26.51%; CGI: +42.71% and +43.95%). Finally, the WoFoSt model output indicates the existence of phenological escape taking place as the century progresses. Both heading and maturity dates were found to shift forward by larger amounts under RCP 8.5 than under RCP 4.5.

As for the functionality of WoFoSt, this study has found the crop simulation model to be highly accurate regarding the development of winter wheat phenology (d=0.92), leaf area index (d=0.79, d=0.81, d=0.88), and soil water content (d=0.74, d=0.76, d=0.83). The crop yield simulation was less accurate than the other outputs, and accuracy varied depending on location (REH: d=0.67, CGI: d=0.76, NEU: d=0.54, SHA: d=0.51, WYN: d=0.6). The model proved to be the most accurate when using location specific simulations. Some issues regarding transferability to and from Changins and the other locations was found. Overall, the model provides promising results and can be optimized even further in the future. Future studies are suggested to use the python version of WoFoSt (Python Crop Simulation Environment PCSE). The python version is more compatible with other data formats and tools, which will allow for faster modelling and data processing.

The uncertainties within climate projections and crop simulation models call for regularly updated studies to ensure future food safety in a changing climate. As a result of our study, we suggest further research be performed on location-specific crop responses to climate change as the century progresses. Additionally, we suggest future research on crop growth in Changins be compared to other locations, to determine potential regional differences in crop growth in Switzerland.

7. References

Asseng, S., Ewert, F., Martre, P. *et al.,* 2015. Rising temperatures reduce global wheat production. *Nature Clim Change* **5**, 143–147. https://doi.org/10.1038/nclimate2470

Boogaard, H., Wolf, J., Supit, I., Niemeyer, S., Ittersum, M., 2013. A Regional Implementation of WOFOST for calculating yield gaps of autumn-sown wheat across the European Union. *Field Crops Research 143*, 130-142. http://dx.doi.org/10.1016/j.fcr.2012.11.005

Boogaard, H., et al. 2021. User's guide for the WOFOST CRONTROL CENTRE 2.1. Wageningen University & Research Centre

Boons-Prins, E. R., G. H. J. De Koning, and C. A. Van Diepen. "Crop-Specific Simulation Parameters for Yield Forecasting across the European Community." CABO-DLO [etc.], 1993.

Bundesamt für Statistik (BFS), 2017. Vom Getreidefeld bis zum Brot: Die Getreideproduktion in der Schweiz. Accessed on 27.01.2022 Taken from: https://dam-api.bfs.admin.ch/hub/api/dam/assets/2160472/master

Ceglar, A., et al., 2019. Improving WOFOST model to simulate winter wheat phenology in Europe: Evaluation and effects on yield. *Agricultural Systems 168*, 168-180. https://doi.org/10.1016/j.agsy.2018.05.002

CH2018 Project Team, 2018. CH2018 - Climate Scenarios for Switzerland, Technical Report, National Centre for Climate Services, Zürich 271 pp.

De Wit, 2017. Crop parameter file for use with the PCSE/WISS implementations of the WOFOST crop simulation model. Accessed on 16.01.2023, URL: https://github.com/ajwdewit/WOFOST_crop_parameters/blob/master/wheat.yaml

De wit, A., Boogaard, H., 2021. A gentle introduction to WOFOST. Wageningen Environmental Research.

Fischer, A.M., 2011. Climate change projections for Switzerland based on a Bayesian multi-model approach. *International Journal of Climatology 32,* 2348-2371. https://doi.org/10.1002/joc.3396

Franch, B., 2015. Improving the timeliness of winter wheat production forecast in the United States of America, Ukraine and China using MODIS data and NCAR Growing Degree Day information. *Remote Sensing of Environment 161*, 131-148. https://doi.org/10.1016/j.rse.2015.02.014

Gouache, D., Le Bris, X., Bogard, M., Deudon, O., Pagé, C., Gate, P., 2012. Evaluating agronomic adaptation options to increasing heat stress under climate change during wheat grain filling in France. *Eur. J. Agron*. *39*, 62–70. https://doi.org/10.1016/j. eja.2012.01.009.

Google maps. (n.d.) Map of Switzerland. Accessed on 10.10.2022. Taken from: https://www.google.com/maps/@46.7887456,8.0800145,8z

Holzkämper, A., Fossati, D., Hiltbrunner, J., Fuhrer, J., 2014. Spatial and temporal trends in agro-climatic limitations to production potentials for grain maize and winter wheat in Switzerland. *Reg Environ Change* 15, 109-122. https://doi.org/10.1007/s10113-014-0627-7

Högy, P., Wieser, H., Köhler, P., Schwadorf, K., Breuer, J., Franzaring, J., Muntifering, R. and 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 Biology, 11:* 60-69. https://doi.org/10.1111/j.1438-8677.2009.00230.x

IPCC, 2019: Summary for Policymakers. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems[P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. In press.

Ludwig, F., Asseng, S., 2010. Potential benefits of early vigor and changes in phenology in wheat to adapt to warmer and drier climates. *Agricultural Systems 103,* 127-136. https://doi.org/10.1016/j.agsy.2009.11.001

Mäkinen, H., Kaseva, J., Trnka, M., Balek, J., Kersebaum, K.C., Nendel, C., Gobin, A., Olesen, J.E., Bindi, M., Ferrise, R., Moriondo, M., Rodríguez, A., Ruiz-Ramos, M., Takác, J., Bezák, P., Ventrella, D., Ruget, F., Capellades, G., Kahiluoto, H., 2018. Sensitivity of European wheat to extreme weather. *Field Crops Res. 222,* 209–217. https://doi.org/10.1016/j.fcr.2017.11.008.

Mishra, S.K., Shekh, A.M., Pandey, V., Yadav, S.B., Patel, H.R., 2015. Sensitivity analysis of four wheat cultivars to varying photoperiod and temperature at different phenological stages using WOFOST model. *Journal of Agrometeorology 17,* 74-79. https://doi.org/10.54386/jam.v17i1.978

Olesen, J. E., Trnka, M., Kersebaum, K. C., Skjelvåg, A. O., Seguin, B., Peltonen-Sainio, P., ... & Micale, F. (2011). Impacts and adaptation of European crop production systems to climate change. *European journal of agronomy*, *34*(2), 96-112.. https://doi.org/10.1016/j.eja.2010.11.003

R Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Rogger, J., Hund, A., Fossati, D., Holzkämper, A., 2021. Can Swiss wheat varieties escape future heat stress? *European Journal of Agronomy* 131. https://doi.org/10.1016/j.eja.2021.126394

Semenov, M.A., Shewry, P.R., 2011. Modelling predicts that heat stress, not drought, will increase vulnerability of wheat in Europe. *Sci Rep* 1, 66. https://doi.org/10.1038/srep00066

Shekhar, C., Singh, D., Singh, R., Rao, V., 2008. Prediction of wheat growth and yield using WOFOST model. *Journal of Agrometeorology (Special issue, Part 2),* 400-402.

Song, Y., Chen, D., Dong, W., 2006. Influence of climate on winter wheat productivity in different climate regions of China, 1961-2000. *Climate Research 32*, 219-227.

Szabó, B., Weynants, M. and Weber, T. K. D. (2021) Updated European hydraulic pedotransfer functions with communicated uncertainties in the predicted variables (euptfv2). *Geoscientific Model Development, 14*, 151–175 doi: 10.5194/gmd-14-151-2021.

Torriani, D.S., Calanca, P., Schmid, S., Beniston, M., Fuhrer, J., 2007. Potential effects of changes in mean climate and climate variability on the yield of winter and spring crops in Switzerland. *Climate Research 34*, 59-69. https://doi.org/10.3354/cr034059.

Wang, L., Feng, Z., & Schjoerring, J. K. (2013). Effects of elevated atmospheric CO2 on physiology and yield of wheat (Triticum aestivum L.): a meta-analytic test of current hypotheses. Agriculture, Ecosystems & Environment, 178, 57-63.

Webber, H., Ewert, F., Olesen, J.E. *et al.,* 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

Weber, T. K. D., Weynants, M., Szabó, B. (2020) R package of updated European hydraulic pedotransfer functions (euptf2). doi: 10.5281/zenodo.4281045.

Willmott, C. J. 1981. On the validation of models. *Physical Geography 2*, 184–194. https://doi.org/10.1080/02723646.1981.10642213

Wolf, J., et al., (2011). Modelling Winter Wheat Production across Europe with WOFOST – The Effect of Two New Zonations and Two Newly Calibrated Model Parameter Sets. *Advances in Agricultural Systems Modeling*. https://doi.org/10.2134/advagricsystmodel2.11

Zarrineh N., Abbaspour K.C., Holzkämper A. (2020). Integrated assessment of climate change impacts on multiple ecosystem services in Western Switzerland. *Science of The Total Environment,* Volume 708, 135212. https://doi.org/10.1016/j.scitotenv.2019.135212.

Zambrano-Bigiarini, M., (2020). hydroGOF: Goodness-of-fit functions for comparison of simulated and observed hydrological time series. doi:10.5281/zenodo.839854, R package version 0.4-0, https://github.com/hzambran/hydroGOF.

Declaration of consent

on the basis of Article 30 of the RSL Phil.-nat. 18

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Bachelor ☐ Master ☑ Dissertation ☐

Title of the thesis: Projecting Climate Change Impacts on Winter Wheat Growth in Switzerland: Calibrating the WoFoSt Crop Simulation Model

Supervisor: PD Dr. Annelie Holzkämper
Co-supervisor: PD Dr. Andreas Hund

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