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Understanding and modelling compound climate and weather events and their impacts on oilseed rape

Doctoral dissertation thesis

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DECLARATION

I hereby declare that the present dissertation work "**Understanding and modelling compound climate and weather events and their impacts on oilseed rape"** is my research work and I have properly acknowledged all the sources of materials used in this dissertation.

Place and date: In Prague; 25.08.2023 **Signature:**

DEDICATIONS

This work is dedicated
to
the precious gifts of my life

My dear son, Raif Ahasan Chowdhury
my mother, Rashida Chowdhury
and all my family members

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Praise be to God the Almighty for the endless blessings.

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ABSTRACT

Winter oilseed rape (*Brassica napus* L., WOSR) is the most essential source of vegetable oil in Europe. Compound agrometeorological events (CEs) are considered to be one of the main factors controlling crop growth and yields under changing climate conditions. To increase the WOSR yield per unit area, utilizing appropriate farming management and sustainable adaptation strategies is now a growing concern. The complex interaction of temperature and precipitation events has major influences on the growth and yield of WOSR. The main focus of the study was to assess the simulation performance of the CSM-CROPGRO-Canola model (incorporated in the Decision Support System for Agrotechnology Transfer (DSSAT) program) for the first time in the Czech Republic. Based on the observed growth and yield parameters of WOSR in the growing seasons 2020–2021 (dry conditions) and 2021–2022 (normal conditions), the study was carried out using three WOSR varieties (Architect, Temptation, and Sněžka) in three different climatic regions (Chrastava, Staňkov, and Vysoká). These varieties were added to the DSSAT crop variety database as new varieties, and their parameters were supplemented based on the experimental field data. Model calibration and evaluation were performed based on the root mean square errors (RMSEs) for each variety. For the Architect, Temptation, and Sněžka, the performance agreement between the observed and simulated yields revealed lower RMSE values of 0.26 t ha^{-1}, 0.04 t ha^{-1}, and 0.07 t ha^{-1}, respectively. Regarding seed oil content, Architect, Temptation, and Sněžka had corresponding RMSEs of 1.18%, 0.67%, and 1.19%, respectively. These results were used to evaluate the model's calibration accuracy and performance, and it was found to be well enough for simulating the selected WOSR varieties for experimental activities. Temperature variations have an impact on the growth and development of WOSR, and the warm temperature region of Chrastava has lower leaf area index (LAI) values for Architect, Temptation, and Sněžka, 3.75, 3.69, and 3.57 m^2 m^{-2}, respectively. On the other hand, Vysoká exhibited higher growth and LAI values as a normal temperature region, with LAI values for Architect, Temptation, and Sněžka of 4.73, 4.78, and 4.69 m^2 m^{-2}, respectively. Under the projected temperature scenario, the highest simulated maximum LAI was recorded from the Vysoká location with the Sněžka variety, while the Chrastava location showed the lowest simulated maximum LAI with the Architect variety.

In addition, the frequency of occurrence of CEs (heat stress during flowering and grain filling stages, black frost, water logging during seeding, and floral bud development) was quantified and evaluated. Projections of CE occurrence for the periods 2021–2040 and 2041–2060 showed that the hot and wet scenarios will experience an increase in heat stress and water logging conditions during flowering and grain-filling stages in all experimental locations. However, the cold and dry scenario will be more vulnerable to a significant rise in the black frost event. Based on the evaluation of the climatic condition, Sněžka and Temptation varieties were found to be the most potential varieties for seed and oil yield, respectively. Moreover, the Vysoká location indicated the most suitable cropping location for WOSR. The findings of this doctoral study will contribute to our understanding of complex interactions among compound events and WOSR crop production dynamics. By utilizing the CSM-CROPGRO-Canola model as a tool to address these effects, we can improve WOSR management strategies.

Keywords: Winter oilseed rape (WOSR), compound events, CSM-CROPGRO-Canola model, climate change, crop simulation, growth, yield, oil

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LIST OF ABBREVIATIONS

WOSR	Winter oilseed rape
FAOSTAT	Food and Agriculture Organization Statistical Database
EU	European Union
UN	United Nations
CE	Compound Events
CZ	Czech Republic
CO_2	Carbon dioxide
RCP	Representative Concentration Pathway
IPCC	Intergovernmental Panel on Climate Change
GS	Growing season
SGS	Sensitive growing season
DSSAT	Decision Support System for Agrotechnology Transfer
BBCH	Biologische Bundesanstalt, Bundessortenamt und CHemical Industry
CSO	Czech Statistical Office
EPIC	Environmental Policy Integrated Climate
APEX	Agricultural Policy Environmental Extender
APSIM	Agricultural Production System sIMulator
STICS	Simulateur mulTIdisciplinaire pour les Cultures Standard
CropSyst	Cropping Systems Simulation Model
GIS	Geographic Information System
BioMA	Biophysical Model Applications
CISTA	Czech Central Institute for Supervising and Testing in Agriculture
HMI-ph	Loamy brown soil-sandy loam soil (light)
Hmm-h	Brown soil typical- clay soil (medium)
LMg-h	Luvism pseudoglea- clay soil (medium)
Nmin	Mineral nitrogen
HTS	Thousand seed weight
.TMX	Temperature maximum
.TMA	Temperature average
.SOL	Soil file
.WTH	Weather file
CHT	Chrastava
STV	Staňkov
VYS	Vysoká
DAP	Days after planting
LAI	Leaf area index
USDA	United States Department of Agriculture
SBuild	Soil build module

ART	Architect
TEM	Temptation
SNK	Sněžka
SAT	Saturated water content
BD	Bulk density
SRGF	Root growth factor
SLPF	Soil fertility factor
Corg	Organic carbon
CEC	Cation exchange capacity
Total N	Total nitrogen
LL	Lower limit of available water to plant
DUL	Drained upper limit or field capacity
Tmin	Minimum temperature
Sc1	Scenario 1
Sc2	Scenario 2
RMSE	Root mean square error
EM-FL	Time between plant emergence and flower appearance (R1) (photothermal days)
FL-SH	Time between first flower and first pod (R3) (photothermal days)
FL-SD	Time between first flower and first seed (R5) (photothermal days)
SD-PM	Time between first seed (R5) and physiological maturity (R7) (photothermal days)
FL-LF	Time between first flower (R1) and end of leaf expansion (photothermal days)
LFMAX	Maximum leaf photosynthesis rate at 30 °C, 350 ppm CO_2, and high light (mg CO_2 m^{-2}-s)
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm2/g)
SIZLF	Maximum size of full leaf (three leaflets) (cm^2)
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell
WTPSD	Maximum weight per seed (g)
SFDUR	Seed filling duration for pod cohort at standard growth conditions (photothermal days)
SDPDV	Average seed per pod under standard growing conditions (#/pod)
PODUR	Time required for cultivar to reach final pod load under optimal conditions (photothermal days)
THRSH	The maximum ratio of (seed/(seed+shell)) at maturity. Causes seed to stop growing as their dry weights increase until shells are filled in a cohort. (Threshing percentage).
SDPRO	Fraction protein in seeds (g(protein)/g(seed))
SDLIP	Fraction oil in seeds (g(oil)/g(seed))
PL-EM	Time between planting and emergence (V0) (thermal days)

EM-V1	Time required from emergence to first true leaf (V1), thermal days
V1-JU	Time required from first true leaf to end of juvenile phase, thermal days
JU-R0	Time required for floral induction, equal to the minimum number of days for floral induction under optimal temperature and daylengths, photothermal days
R7-R8	Time between physiological (R7) and harvest maturity (R8) (days)
RWDTH	Relative width of this ecotype in comparison to the standard width per node (YVSWH)
RHGHT	Relative height of this ecotype in comparison to the standard height per node (YVSHT)
LAImax	Leaf area index maximum
SWI	Soil Water Index
SSM	Surface Soil Moisture

1. INTRODUCTION

Winter oilseed rape (*Brassica napus* L., WOSR) is the third largest oilseed crop in the world and is mainly grown for edible oil, biofuel, and livestock feed (Wallenhammar *et al.,* 2022; FAOSTAT, 2022). WOSR is a significant contributor of biofuel and crop-based oil to both the European Union (EU) and worldwide. Almost 80% of the EU's biofuel production comes from oilseed rape (Ouvrard and Jacquemart, 2019). Furthermore, FAOSTAT (2021) reported that 16% of the world's crop-based oil production is derived from oilseed rape. 16% of the world's crop-based oil production is derived from oilseed rape. With major producing nations like Germany, Poland, France, Italy, and the Czech Republic (CZ), WOSR is the most important source of vegetable oil in Europe (Pullens *et al.,* 2019). Sunflowers, oilseed rape, and soybeans currently dominate the worldwide oilseed market (Wittkop *et al.,* 2009). According to Zanetti *et al.* (2021), WOSR is the major oilseed crop, followed by sunflower and other minor crops like camelina and linseed, in the context of European agriculture. The CZ is one of the major producers of oilseed rape, with an annual production of 1.2 million tonnes in 2021 (FAOSTAT, 2022). It is estimated that global food crop production needs to be increased by approximately 30% to feed around 9.7 billion people globally by 2050 (UN, 2022). Considering this ever-increasing population, the demand for high-quality seed oils will continue to rise, and the oilseed market will need to meet the demands with alternatives (Falcon *et al.,* 2022).

This increasing demand can be achieved through suitable farming management, sustainable adaptation strategies, and the selection of potential varieties to enhance the crop yield per unit area (Newmann *et al.,* 2010). However, adverse agrometeorological events continue to have impacts on global agricultural productivity despite advancements in crop management and adaptation strategies (Cohn *et al.,* 2016). Due to its strong reliance on the climate, agriculture is particularly susceptible to the effects of climate change. Temperature and precipitation variations have the greatest impact on oilseed rape productivity due to climate change. Oilseed rape growth and yield are determined by the complex interaction of various environmental factors, such as soil type, water availability, climatic conditions, and fertilizer availability (Weymann *et al.,* 2015; Asare and Scarisbrick, 1995; Mendham *et al.,* 1981).

Crop productivity is predicted to significantly decline as a result of the projected 2.9°C to 5.5°C increase in global temperature by 2060. This might have radical effects on the availability of food, oil, and fiber supplies (Arshad *et al.,* 2021). Compound events (CEs) function as constraining factors regulating crop growth and yields (Potopová *et al.,* 2020, 2023a; Ben-Ari *et al.,* 2018; Ray *et al.,* 2015). The CEs are quantified as crop yield-limiting factors by air temperature, amount and distribution of precipitation, soil moisture content, and evapotranspiration (Pulido-Moncada *et al.,* 2021, Potopová *et al.,* 2021a-b).

According to the climate projections, the average annual air temperature in the CZ might increase between 1.0 and 4.5 °C (in the RCP4.5 scenario) or 2.5 and 5.5 °C (in the RCP8.5 scenario) as compared to 1971–2000 (Rulfová *et al.,* 2021; Potopová *et al.,* 2018). A temperature increase up to 2.0 °C by the middle of this century might be possible (Ceglar *et al.,* 2019; Jacob *et al.,* 2018). The anthropogenic increase in atmospheric CO_2 concentrations may result in a decline in stomatal conductance (Ainsworth and Rogers, 2007), which might reduce canopy transpiration and enhance the water status of soil and plants (Bernacchi *et al.,* 2007). Enhanced CO_2 concentrations might improve water use efficiency, but they may also have the opposite effect due to temperature rises that accelerate evapotranspiration (Jaggard *et al.,* 2010).

Crops may experience complex interactions between high temperatures and CO_2 concentrations, as well as unpredictable precipitation patterns that are impacted by a variety of environmental drivers (Walker and Schulze, 2008). Additionally, the soil moisture projections showed that the area and intensity of soil drying (drought) are strongly dependent on crop growing seasons (GS), sensitive growing seasons (SGS), and catchments (Ruosteenoja *et al.,* 2018; Samaniego *et al.,* 2018). At the catchment level, soil moisture content, crop types, crop water availability, and soil properties over land will affect the evaporation and plant-soil dynamics (Merk *et al.,* 2021). However, the rate of change will vary with available energy, wind speed, air, temperature, and air humidity (Eshonkulov *et al.,* 2019).

In the case of precipitation, projected future changes may enhance uncertainty at regional scales, which can obstruct the WOSR growing season and affect growth and yields (Papadimitriou *et al.,* 2019). Under such conditions, crop models and decision support systems can be useful tools for researchers, teachers, scientists, extension personnel, policymakers, and planners to help and support the application and evaluation of sustainable and long-term alternative management practices (Nasim *et al.,* 2016). Crop modelling can be used to analyze the impact of climate change on existing cropping systems (Lenz-Wiedemann *et al.,* 2010). The utilization of crop models is a promising possibility for the integration of physiological understanding of crop features. It allows for the examination of potential growth and significant production restrictions in varying environments and management scenarios (Saseendran *et al.,* 2010). The CSM-CROPGRO-Canola model is a generic crop growth model incorporated with the Decision Support System for Agrotechnology Transfer (DSSAT) program, which is used globally to simulate crop development and yield characteristics of oilseed rape under current and projected climatic conditions (Hoogenboom *et al.,* 2019b; Jones *et al.,* 2003).

This work aims to test and evaluate the CSM-CROPGRO-Canola model combined with the climate model to simulate the WOSR growing stages and yield estimations under the current and projected climatic conditions at three different experimental locations in the CZ.

1.1 Hypotheses of the research

1. The tendency of increases in the intensity and frequency of compound weather events related to climate change will lead to higher yield variability and reduce the qualitative parameters of WOSR in the main producing regions.
2. Temperatures will change due to climate change and will therefore affect the development and growth of WOSR.
3. Drought stress during the early stages of crop growth can lead to unfavorable conditions that will affect crop establishment and subsequent growth, thus reducing the success of crop establishment.

4. The joint precipitation and temperature extreme events during the seed-filling period may affect yields of WOSR, and therefore climate change may affect crop yield stability.

1.2 Objectives of the research

1. Modelling the performance of oil-seed rape varieties in relation to compound climate/weather events in the Czech Republic.
2. To evaluate the response of oilseed rape yield and oiliness parameters to weather factors.
3. To quantify the vulnerability of the winter varieties of oilseed rape to climate change by the integration of climate models and crop models.
4. To identify which aspects of WOSR crop production are most affected by projected changes in climatic conditions.

2. LITERATURE REVIEW

2.1 Oilseed rape: an important oil crop

According to the United Nations, the global population is projected to reach 9.7 billion and 10.4 billion by 2050 and 2100, respectively (UN, 2022). With the world population continuing to rise, there will be a constant need for high-quality seed oils. As a result, the oilseed market will have to explore alternative ways to meet these demands. Vegetable oils are considered excellent sources of edible oil as well as renewable industrial oils (Wallenhammar *et al.,* 2022). Besides being the second largest oilseed crop globally, WOSR is also considered the third and second largest source of vegetable oil and protein meal in the world, respectively (Wallenhammar *et al.,* 2022). The scientific classification of oilseed rape is shown in Figure 1.

Kingdom: Plantae
Clade: Angiosperms
Order: Brassicales
Family: Brassicaceae
Genus: Brassica
Species: *Brassica. Napus* L.

Figure 1. Scientific classification of oilseed rape

According to the BBCH (Biologische Bundesanstalt, Bundessortenamt und CHemical Industry) system (Meier *et al.,* 2009), oilseed rape has nine principal growth stages (Figure 2). Despite the fact that the principal growth stages are shown in chronological order, the beginning of each stage is not dependent on the completion of the preceding stage. Hence, several stages might overlap (Meier *et al.,* 2009). The main growth stages include germination and emergence (GS0: 0-09 days), leaf development (GS1: 10–19 days), side-shoot formation (GS2: 20–29 days), stem elongation/extension (GS3: 30-39 days), inflorescence/flower-bud emergence (GS5: 50–59 days), flowering (GS6: 60–69 days), pod/seed (fruit) development (GS7: 71–79 days), pod/seed (fruit) ripening (GS8: 80–89 days), and senescence (GS9: 90–99 days) (Meier *et al.,* 2009).

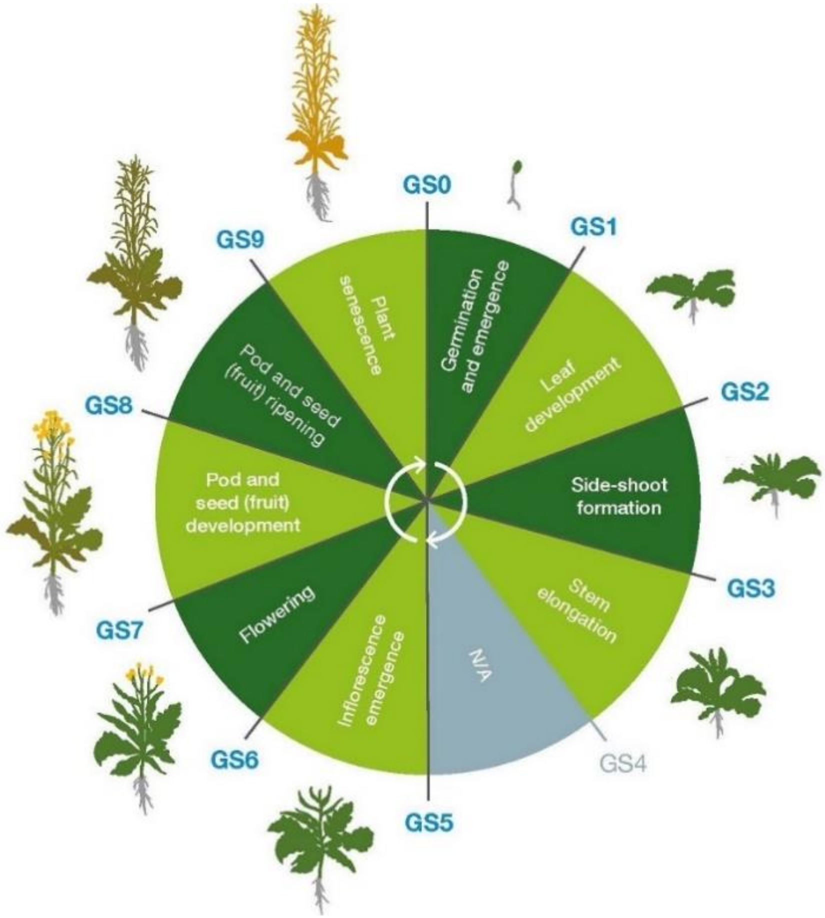

Figure 2. The growth stages of oilseed rape according to the BBCH system (Meier *et al.,* 2009)

Oilseed rape is mainly cultivated in the winter months over most of Europe and Asia (Beszterda and Nogala-Kałucka, 2019), as this crop requires vernalization for flowering (O'Neill *et al.,* 2019). Generally, winter oilseed rape is sown in autumn, but it remains in a leaf rosette on the soil surface during the winter. Flowering starts in the late spring, and ripening occurs until mid-summer (Rahman *et al.,* 2018). In Europe, winter oilseed rape is mainly grown as an annual break crop in three- to four-year rotations with cereals such as wheat and barley (Hegewald *et al.,* 2018). Generally, winter oilseed rape can be cultivated on a variety of well-drained soils with a pH range between 5.5 and 8.3 (Hennig *et al.,* 2021). It is primarily wind-pollinated, but it can also be pollinated by bees. Europe is the largest region of oilseed rape producers (35%) globally (FAOSTAT, 2022). The Czech Republic is currently the world's tenth-largest oilseed rape producer. Between 2000 and 2020, the Czech Republic produced an average of approximately 1.07 million tonnes of oilseed rape (FAOSTAT, 2022).

2.2 Status of oilseed rape production in the last decade

In the last decade, there has been a significant rise in both the cultivated area and production of oilseed rape worldwide. According to FAOSTAT 2022, since 2010, the global production of oilseed rape has increased from ~59 million tons to ~72 million tons (~1.21X), whereas the cultivated area has increased from ~32 million hectares to ~35 million hectares (~1.11X). The yield of oilseed rape was significantly improved in the early 1990s by enhancing the performance of hybrid varieties. Single-cross hybrids were popular across all oilseed-growing regions, including Europe. Particularly in the last 20 years, new oilseed rape varieties with distinct qualitative (fatty acid profile, fiber content), quantitative (yield), and phenotypic (growth rate) characteristics have been released to the market (Wittkop *et al.,* 2009). Oilseed rape is the second most significant winter crop in the Czech Republic, occupying 15.7% of total cultivable land (CSO, 2022).

2.3 Compound weather events during WOSR production

Numerous environmental conditions influence WOSR cultivation, which may have a substantial impact on yield and productivity (Paulauskas *et al.,* 2013). The compound climatic events have been found to negatively impact WOSR, impeding its growth and ultimately lowering the yield. Low temperatures and temperature changes cause serious hazards to WOSR (Jankowska and Bortkevich *et al.,* 2019). Researchers have developed a range of predictive models to understand and predict climatic impacts on the growth and yield attributes of WOSR. These models work based on numerous climatic factors such as air temperature, relative humidity, precipitation, and sunshine duration (Koch *et al.,* 2007).

Increased CO_2 levels have been shown to support WOSR by increasing yields and biomass, while higher temperatures were found to be a significant factor in the loss of biomass and yield (Clausen *et al.*, 2011). Drebenstedt *et al.*, (2020) investigated that the combination of drought and heat significantly reduces the leaf area and yield of winter oilseed rape. Conversely, Cold damage (below freezing <°C) is a major event when it comes to winter oilseed rape, particularly during the early stages of development. This extremely low temperature has the potential to damage plant cells, prevent significant physiological processes, and inhibit plant growth and development. As a result, frost damage can reduce biomass accumulation and oil content at harvest (Rys *et al.*, 2020). Furthermore, Wollmer *et al.* (2018) have found that heavy rainfall can increase soil erosion, runoff, and disease, which leads to a decrease in winter oilseed rape yields.

Photo-thermal factors controlled the growth stages of WOSR from emergence to flowering, whereas temperature changed from flowering to maturity (Xu *et al.*, 2021; Arjona *et al.*, 2020). The longest growth phase of WOSR involves juvenile growth, emergence, overwintering, and stem elongation. For seedling germination and emergence, optimal field conditions are crucial. Temperatures below 10°C might lead to poor germination, whereas extremely dry and high temperatures might negatively impact seedling emergence (Matar *et al.*, 2021). Due to inadequate plant establishment, the early developmental stages are highly susceptible and frequently decrease the seed yield of WOSR (Yang *et al.*, 2014).

Despite substantial biomass production during flowering, excessive precipitation during the pre-flowering phase may have a negative impact on yield (Takashima *et al.*, 2013). Due to reduced total leaf area development and a lower rate of photosynthesis, plants may suffer at the flowering stage (Balodis and Gaile, 2016). Lack of available water during the post-flowering period reduces yield as canopy transpiration cannot be sustained (Weymann *et al.*, 2015). WOSR growth stages play a key role in yield estimation models, and the main parameters impacting WOSR growth stages and yield are environmental conditions such as temperature, irradiation, and precipitation (Weymann *et al.*, 2015). Changes in temperature and precipitation are the worst compound weather events for WOSR production. Different crops are known to be affected by these two elements differently.

In all stages of oilseed rape's growth, temperature plays a critical role in both development and growth (Rathke *et al.*, 2006). Temperature is crucial for germination and emergence under ideal field conditions. Extremely low or high temperatures have a deleterious impact on the emergence of WOSR during the germination stage (Brown *et al.*, 2019). While heat and water stress are predicted to have a negative influence on yields and productivity in Southern Europe, longer growing seasons and generally abundant rainfall are predicted to boost total yields in Northern Europe (Webber *et al.*, 2018). Although WOSR is the principal oilseed crop in Europe, the majority of the crop's production is concentrated in Germany, Poland, Italy, the Czech Republic, and France (van Duren *et al.*, 2015; Monfreda *et al.*, 2008). Temperature and precipitation during the seed-filling period were found to be adversely connected with WOSR yields, according to experimental regression-based analyses (Sharif *et al.*, 2017; Peltonen-Sainio *et al.*, 2010). In addition, drought stress may also play an important role in WOSR productivity and yield stability. Studies have shown that drought stress during the early stages of crop growth may create unfavorable conditions that ultimately impact crop establishment and subsequent growth (Ahmad *et al.*, 2021). Prolonged wet periods, however, may also lead to improper seed beds, which would ultimately damage crop establishment (Rathke *et al.*, 2006).

2.4 Climate change impacts on WOSR production

Effects of climate change (e.g., drought or wet) have direct and indirect effects on crop establishment and subsequent growth. Different experimental studies have shown that the effects of climate change during the seed formation stage can result in reduced crop yield in WOSR (Sharif *et al.,* 2017). Temperature is a significant factor in the physiological growth stages of WOSR (Weymann *et al.,* 2015). Climate change is causing global temperatures to rise, which can lead to elongated stem growth in cold-tolerant varieties of WOSR and make them more vulnerable to frost damage in colder regions. According to prediction models, crop yield may be impacted by the state of global climate change, which may also result in changes to agricultural production regions and cropping patterns (Elsgaard *et al.,* 2012). In European WOSR, greater yield deviations were noticed with adverse climatic events than cultivar differences (Nowosad *et al.,* 2016).

Particularly, climatic events such as light intensity, photoperiod, atmospheric temperature, and precipitation are considered crucial influences for crop yield instability during the physiological growth stages (Beszterda and Nogala-Kałucka, 2019; Morrison and Stewart, 2002; Habekotté, 1997). For example, extreme heat and cold during the seed-filling stage have demonstrated significant yield variations in central Europe (Weymann *et al.,* 2015).

2.5 Crop modelling approach and application of crop growth models for WOSR

There are numerous growth models for predicting the production of oilseed rape under various climatic conditions. The Decision Support System for Agrotechnology Transfer (DSSAT) program, which includes dynamic crop growth simulation models for more than 42 crops, is a helpful tool for simulating growth, development, and yield as a function of soil-plant-atmosphere dynamics (Hoogenboom *et al.*, 2019a). The Environmental Policy Integrated Climate (EPIC) is a cropping systems model used to predict the impacts of soil, water, nutrient, and pesticide movements with their combined effects on soil loss, water quality, and crop yields (Williams *et al.*, 1984). Agricultural Policy Environmental Extender (APEX) is a modelling tool that can be divided into relatively homogeneous soil, land use, management, and weather conditions. It includes directing water, sediment, nutrients, and pesticides across compound landscapes and channel systems to the watershed outlet (William, 2002).

The Agricultural Production System sIMulator (APSIM) is a crop growth model that was developed to simulate biophysical processes in agricultural systems. The model can forecast various crop yields based on soil, climate, and crop management variables. The APSIM-Canola module was described and incorporated into the APSIM model by Robertson and Lilley (2016). The BRASNAP-PH model was developed to predict the temperature and photoperiod-related events at the emergence, onset, and end of flowering and maturity of WOSR (Habekotte, 1997). The STICS (Simulateur mulTIdisciplinaire pour les Cultures Standard) model is a dynamic, generic, and robust model aiming to simulate the soil-crop-atmosphere system (the Institut national de la recherche agronomique).

The HERMES model is an agro-ecosystem model that can simulate soil-crop interactions with an emphasis on water and nitrogen-based processes (Kersebaum, 2007; 2011). According to Klik and Eitzinger (2010), the model is robust and able to recreate inter-annual variability in yields, biomass, and soil processes under a variety of field crop rotations. The HERMES model has the ability to assess mitigation and adaptation strategies as well as forecast changes in agricultural productivity and soil processes under climate change circumstances (Smith and Olesen, 2010). The LINTUL-BRASNAP is a useful tool for identifying the major crop factors that affect leaf area development, flower density, and subsequent photosynthesis during the critical period of seed set in winter oilseed rape (Habekotté, 1997). The HUME-OSR is a process-based model that can simulate physiological processes based on radiation interception (IR) and captures the majority of important processes contributing to crop productivity (Böttcher *et al.,* 2020).

CropSyst (Cropping Systems Simulation Model) is a multi-year, multi-crop, daily time-step crop growth model linked to GIS (Geographic Information System) software. To estimate agro-meteorological variables (Bregaglio *et al.*, 2011) and to evaluate the quality of agricultural products (Cappelli *et al.,* 2014), the CropSyst model was reorganized in the BioMA-Biophysical Model Applications platform (Donatelli *et al.,* 2012) for developing and running biophysical models on generic spatial components to simulate crop development and yield under potential and water-limited environments to estimate crop suitability to the environment (Confalonieri *et al.,* 2013). A few crop parameters, such as date of sowing, genetic coefficients of cultivar, soil profile information (e.g., soil texture, depth), fertilizer and irrigation management, tillage, and atmospheric CO_2 concentration, are required to run the model for simulating the impact of CO_2 concentration on plant growth and yield (Tubiello *et al.,* 2007).

3. MATERIALS AND METHODS

Winter oilseed rape faces changing biotic and abiotic stresses linked to climate change. The proposed objectives, therefore, undertook a novel examination of the dual concept of crop losses and compound climate/weather events during the growing cycle of winter oilseed rape under various soil and climatic conditions. The methodology of the thesis is based on the relationship between climate models and the crop growth model, as well as experimental research tools for predicting the development of the production process of WOSR in response to climate change. A chosen growth model (DSSAT) was utilized to investigate the relationship between the soil, plant, and atmosphere. The results were confirmed through an experiment conducted in the field. The study consists of two scientific research activities:

3.1 Experimental activities

The experiments were carried out in collaboration with the Czech Central Institute for Supervising and Testing in Agriculture (CISTA): the establishment of field trials, detailed monitoring of environmental conditions, growth, development, and yield parameters of WOSR, and the creation of a database to help parameterize crop models. The study was conducted between September and August of 2020–2021 and 2021–2022, respectively, in the Czech Republic in the Chrastava, Staňkov, and Vysoká regions under various soil and climatic conditions (Fig. 3). The following are the general characteristics of the study locations: - *Chrastava:* The Chrastava study location is considered a warm climatic region with an average altitude of 345 m (above sea level, a.s.l.). The long-term (1961–2021) average temperature and long-term average total precipitation are 8.0 °C and 738 mm, respectively. The soil type at this location is HMI-ph (loamy brown soil-sandy loam soil (light)). *Staňkov: The* Staňkov study location is a moderately warm climatic region with an average altitude of 370m (a.s.l.). The long-term average temperature and long-term average total precipitation are 8.1 °C and 537 mm, respectively. The soil type is Hmm-h (brown soil typical- clay soil (medium)). *Vysoká: The* Vysoká study location is a cold region with a long-term average temperature of 7.1 °C and a long-term average precipitation of 611 mm. The average altitude of this location is 580 m (a.s.l.) with the typical soil type LMg-h (Luvism pseudoglea-clay soil (medium)).

To evaluate the response of oilseed rape varieties to compound events, we included crop phenological, yield, and qualitative parameters (beginning and the end of flowering, maturity, lodging, plant length, overwintering, thousand seed weight, yield, and oiliness) in the model. Meteorological conditions during the experimental period in terms of extreme precipitation and temperature anomalies were used as an important site-specific input parameter. At the CISTA experimental stations, the cultivated crops were observed in terms of sowing and harvesting, fertilization (date, amount, and type of fertilizer), yields, above-ground biomass at harvest, soil content of mineral N (Nmin) at different soil depths, and the N content within the above-ground biomass.

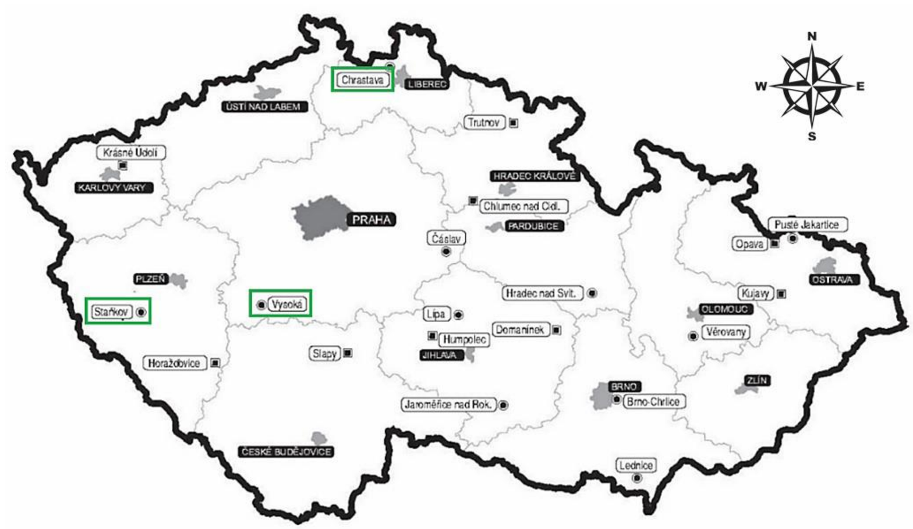

Figure 3. Experimental field locations

3.2 Selection of WOSR varieties

Winter oilseed rape is a suitable model crop since it is sensitive to temperature and frost in the cold season of the year, as well as to precipitation and drought during the growing season. This work is a response to the findings of testing the modern WOSR varieties adapted to ongoing changes in both market demands and climatic conditions. The plants were tested for yield, phenological, and quality parameters concerning meteorological factors. To understand and evaluate the responses of WOSR crops to compound weather events, three WOSR varieties were used in this experimental study, namely Architect, Temptation, and Sněžka. The varieties were selected based on their agronomic characteristics (table 1).

Table 1. Potential agronomic characteristics of the selected WOSR varieties

Yield and seed quality in dry matter	Architect	Temptation	Sněžka
Yield (t ha^{-1})	5.1-6.1	5.4-6.1	4.4-6.4
Crude protein content (%)	19.7	19.3	19.8
Potential Oil content (@ 9% moisture)	45.0	46.0	44.3
HTS (g @ 12% humidity)	5.0	4.3	4.6
Resistance characteristics			
White crucifer rot	5.2	5.1	5.8
Blacking of crucifer stalk	5.7	6.1	6.4
Alternaria spotting of crucifers (Black oilseed rape)	6.9	6.9	7.6
Complex root disease of Cruciferous	6.3	6.1	6.4
Fatty acid composition (% of total fatty acids)			
Saturated fatty acids	5.8	6.2	6.2
Oleic acid	62.5	65.5	65.2
Linoleic acid	19.1	17.3	17.4
Alpha-linolenic acid	9.2	7.7	7.8
Erucic acid	<0.05	<0.05	<0.05
Glucosinolate content	15.9	14.7	12.4

*Explanatory notes: 9 = best value, favorable property; 1 = worst value, substandard property; HTS= Thousand seed weight

ARCHITECT

Maintainer:
Limagrain Europe, Biopôle Clermont-Limagne, Rue Henri Mondor, 63360 Saint Beauzire, France

Authorized representative:
Limagrain Central Europe S.

- The Architect variety is a semi-late pollen-fertile hybrid variety with minimal erucic acid and low glucosinolate content.
- Plants are medium to tall and resistant to lodging before harvest.
- The variety is less to moderately resistant to foma black spot, less to moderately resistant to white rot, moderately resistant to alternaria blight, and moderately resistant to verticillium wilt.
- Seed and oil yields in both warm and cool growing areas are high.
- The thousand seed weight ranges from medium to high.
- Seed oil content is moderate to high, and the oil content of fatty acid is standard. Seed N-substance is low to medium-high.

TEMPTATION

Maintainer:
Deutsche Saatveredelung AG,
Weissenburger Str. 5, 59557 Lippstadt,
Germany

Authorized representative:
OSEVA PRO s.r.o., Jankovcova
938/18, 170 37 Prague 7

- The Temptation variety is a semi-late pollen-fertile hybrid variety with low erucic acid and glucosinolate content.
- The plants are medium-tall and moderately resistant to lodging before harvest.
- The variety is moderately resistant to foma black spot, less resistant to white rot, moderately resistant to alternaria blight, and verticillium wilt.
- Among the hybrid varieties, the seed yield is high, with a higher oil yield.
- Thousand seed weight is low to medium.
- Seed oil content is high and the oil content of the different fatty acids is standard. Seed N-substance is low.

SNĚŽKA

Maintainer: SEMPRA PRAHA a.s.,
U topíren 2/860, 170 41 Prague 7

- The Sněžka variety is a semi-late variety with minimal erucic acid and low glucosinolate content.
- Plants are mostly medium-tall and resistant to lodging before harvest.
- The variety is moderately resistant to foma black spot, moderately resistant to white rot, moderately resistant to alternaria blight, and moderately resistant to verticillium wilt.
- Within the range of line varieties, seed and oil yields in both warm and cool growing areas are very high.
- The thousand seed weight is medium-high.
- Seed oil content is moderately high, oil content of individual fatty acids is standard with low to medium-high seed N-substance.

3.3 Datasets

Weather data

The weather dataset for the study was collected from three automated meteorological stations of the Czech Hydro-meteorological Institute, namely U2LIBC01 (for Chrastava), L1STAN01 (for Staňkov), and P1PRIB01 (for Vysoká). The geographical coordinates and elevations of the stations for Chrastava, Staňkov, and Vysoká locations are 50° 46' 8.2704" N 15° 1' 27.4692" E (397.72 m a.s.l.), 49° 41' 37.3308" N 14° 0' 57.0132" E (362 m a.s.l.), and 49° 41' 37.3308" N 14° 0' 57.0132" E (555 m a.s.l.) respectively. The weather data collected daily encompassed precipitation (RAIN-mm), maximum air temperature (Tmax-°C), minimum air temperature (Tmin-°C), and solar radiation (SRAD-$MJm^{-2}day^{-1}$) weather evaluation and modeling activities. The baseline dataset for the crop model weather input module starts on January 1, 2010, and extends through December 31, 2022. For winter oilseed rape (WOSR) simulation modeling during the experimental years, weather datasets for 2020–2021 (September 2020–July 2021) and 2021–2022 (September 2021–July 2022) were used according to the crop growing seasons. The weather data were incorporated into the WeatherMan module in the DSSAT model (Table 2).

Table 2. Structure of weather data input into the WeatherMan module of the DSSAT program

Date	**Precipitation**	**Maximum daily temperature**	**Minimum daily temperature**	**Solar radiation**
W_DATE	**RAIN**	**TMAX**	**TMIN**	**SRAD**
dd/mm/yyyy	**mm**	**°C**	**°C**	**$MJm^{-2}day^{-1}$**
01/07/2021	39	18.9	12.4	10.7
02/07/2021	5.7	18.2	10.8	14.0
03/07/2021	0.0	22.3	12.8	19.2
04/07/2021	0.0	23.3	9.0	11.8
05/07/2021	2.6	22.9	12.3	10.2
06/07/2021	0.0	26.8	14.2	14.2
07/07/2021	24.5	19.7	13.6	21.2
08/07/2021	29.5	21.8	11.0	19.2
09/07/2021	9.2	22.9	14.4	21.7
10/07/2021	0.0	23.6	11.9	18.8

To quantify non-optimal agroclimatic growing conditions concerning physical and biological stressors, a total of seven agroclimatic indices were calculated. The agroclimatic indices are as follows:

- Heat stress during flowering – a 2-day period of maximum temperature above +35 °C from the onset of flowering to the end of flowering.
- Black frost – the event is triggered when the Tmin (minimum daily temperature) is equal to or below −18 °C for at least one day with no or very limited snow cover (less than 1 cm of freshly fallen snow).
- Late frost – event is triggered when the Tmin is equal to or below −2 °C after the start of a time window determined as the period when the mean air temperature is continuously 10 °C (for at least five days) and does not drop below 10 °C for more than two days in a row.
- Heat stress during grain filling – the event is triggered when the Tmax (maximum daily temperature) is above+35 °C for at least two days during the period from flowering to maturity.
- Water logging during seedling and floral bud development – the event is triggered if the soil moisture is at or above the field capacity for more than 30 days from sowing to anthesis. Days with a mean temperature below 3 °C are not counted.
- Drought stress during flowering – actual water content is less than 40% of plant's available water content for ten consecutive days.
- Adverse sowing conditions – event is triggered when there are no more than three days during the sowing window (sowing date±15 days) with the soil moisture in the top layer below 90% but above 5% and rain on the given day is below 5mm and not more than 10mm on the preceding day.

The monthly data were collected based on the long-term monthly mean and for the experimental years. The monthly dataset was processed for temperature and rainfall variations from weather event categorizations (e.g., warm-dry, warm-wet, cold-dry, cold-wet, etc.). For temperature, the deviations were from the long-term monthly mean (Δt=t-tLTM) calculated (mean monthly temperature for the long-term (tLTM) minus mean monthly temperature during the growing season (t)). For rainfall, the monthly percentage of long-term rainfall (r*) was calculated (total monthly rainfall for the long-term = total monthly rainfall during the growing season × 100). Based on the evaluation of weather conditions from both the growing seasons 2020–2021 and 2021–2022, the two experimental years were categorized into dry weather conditions (2020–2021) and normal weather conditions (2021–2022) (Table 3).

Table 3. Evaluation of weather dataset during the growing seasons

Months	2020-2021 Temperature category	2020-2021 Moisture category	2021-2022 Temperature category	2021-2022 Moisture category
Chrastava				
September	warm	normal	warm	dry
October	warm	wet	normal	normal
November	normal	severe dry	normal	normal
December	severe warm	severe dry	normal	normal
January	normal	wet	warm	normal
February	normal	normal	severe warm	severe wet
March	normal	normal	normal	extreme dry
April	cold	normal	normal	normal
May	cold	wet	warm	dry
June	extreme warm	normal	extreme warm	wet
July	warm	severe wet	normal	dry
Staňkov				
September	normal	normal	warm	severe dry
October	normal	normal	cold	dry
November	normal	severe dry	normal	normal
December	warm	normal	normal	normal
January	normal	severe wet	warm	normal
February	normal	wet	severe warm	normal
March	normal	normal	normal	normal
April	cold	dry	normal	normal
May	cold	severe wet	warm	normal
June	extreme warm	normal	extreme warm	wet
July	normal	wet	warm	dry
Vysoká				
September	normal	wet	normal	severe dry
October	normal	wet	normal	dry
November	normal	dry	normal	wet
December	normal	dry	normal	normal
January	normal	wet	normal	normal
February	normal	wet	severe warm	dry
March	normal	normal	normal	normal
April	extreme cold	normal	cold	normal
May	severe cold	wet	warm	normal
June	warm	severe wet	warm	severe wet
July	cold	wet	normal	normal

In this study, the current climate conditions in the growing season 2021-2022 (the climate when the field trials were conducted) were considered (Sc1), and the environmental module of the crop model was adjected according to the Representative Concentration Pathway (RCP8.5) was considered as the future scenarios (Sc2) for the period 2021-2040. Under Sc2, the average temperature is projected to increase by +2 °C from the current global average temperature, and the concentration of CO_2 will be increased to 936 ppm, which will double the current global average CO_2 concentration of 421 ppm.

Crop data

The land preparation of all the locations started by the first week of mid-August to mid- September (autumn), with a plowing depth of 25–30 cm. The sowing of WOSR started 1-2 days after the land preparation at a planting depth of 2 cm. Each experimental plot consists of 10–11 rows with a seed rate for sowing varying from 2.7 to 4.05 kg ha^{-1} and a row spacing of 12.5 cm (Fig. 4).

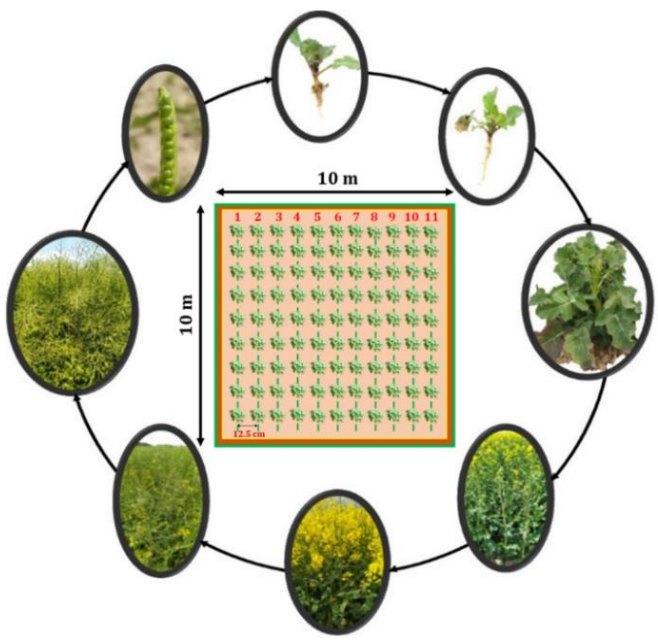

Figure 4. Crop phenological design of the experimental plot

Nitrogen fertilizer was applied as a basal dose by the time of land preparation and by the vegetative growth stage from March to April. To evaluate the CSM-CROPGRO-Canola model, the required standard DSSAT files (*.TMX, *.TMA, *.SOL, *.WTH) for climate, soil, crop growth, management, and yields were collected from all three study locations.

The calibration of a crop model depends on phenological experimental data, which is also essential to integrating portioning. Accordingly, the field data collection for crop physiological analysis started in the first week of November 2020 (1st-year experiment) and 2021 (2nd-year experiment), when the plants were approximately 50–60 days old with an approximate population of 53–65 plants per m^2. Crop phenology was monitored biweekly using the BBCH scale (Meier *et al.,* 2009). Plant phenology (%) was determined as a ratio of plants recorded within each phenological stage to the total number of plants in the experimental field. Leaf area was calculated by infrared image analysis using Adobe Photoshop software (raw images were taken by infrared photographs with an 8-megapixel resolution). The fresh weight and dry weight (oven at 105 °C) of the biomass partitioning (leaf, stem, and genetic part) of the sample plant were taken. Crop management data for WOSR varieties, such as sowing date, anthesis day, first fruit set day, harvest maturity day, and leaf area index, were obtained during the growing seasons from the experimental locations (Table 4). The field preparation began in late August. The final harvest occurred in early September.

Table 4. Crop management dataset for calculation of growth coefficient for oilseed rape varieties

Parameters	CHT			STV			VYS		
	ART	**TEM**	**SNK**	**ART**	**TEM**	**SNK**	**ART**	**TEM**	**SNK**
Flowering date (days after planting)	247	242	244	246	240	242	244	246	243
Plant height (m)	1.58	1.49	1.47	1.40	1.38	1.27	1.39	1.40	1.41
Yield (t ha^{-1})	5.12	5.63	4.40	5.11	5.41	4.93	6.15	6.13	6.40
Leaf Area Index, maximum (LAI_{max})	2.84	3.39	2.58	3.54	2.68	2.86	3.10	3.43	2.94
First pod formation date (days after planting)	251	250	254	250	248	253	251	253	250
Harvest maturity date (days after planting)	321	320	320	319	317	316	332	331	330
Seed yield (kg ha^{-1})	3.45	2.79	4.04	3.45	2.79	4.04	3.45	2.79	4.04
Seed oil content (%)	49.29	51.31	49.08	49.29	51.31	49.08	49.29	51.31	49.08
Thousand seed weight (g)	4.33	3.58	4.31	4.09	3.66	4.16	4.72	4.23	4.39
Harvest date (days after planting)	325	323	327	322	320	321	335	334	335

*CHT-Chrastava; STV-Staňkov; VYS-Vysoká; DAP-Days After Planting; LAI-Leaf Area Index

Soil data

The soil data from the experimental sites were collected from the field based on the soil layer depths (10 cm each up to 60 cm) by using the soil standard sampling materials and keeping the soil samples in airtight zip bags and soil cores for laboratory analysis. The physical property analysis of the soil sample was done by the textural group categorization based on the particle's combination (percentage of clay, silt, and sand) and then organized the textural groups (e.g., loam, sandy loam, etc.) using the Soil Textural Calculator by the USDA. The hydro-physiological properties were calculated by using chemical analysis of the core soil samples, and specific soil parameters (lower limit, drained upper limit, saturation, drainage coefficient, and runoff curve number) were estimated from the measurement of the soil profile (Table 5). The soil profiles for Chrastava, Staňkov, and Vysoká sites were characterized as loamy brown soil-sandy loam soil (light), brown soil typical-clay soil (medium), and Luvism pseudoglea-clay soil (medium), respectively. The input for the soil module (SBuild) includes data on the composition of the soil, such as the percentages of clay, silt, and sand particles, as well as the amount of organic carbon present. Other parameters include the cation exchange capacity, pH level, slope of the land, albedo (reflectivity), color, drainage, drained upper limit (DUL), total soil nitrogen content, lower limit (LL), saturated water content (SAT), hydraulic conductivity, bulk density, root growth factor (SRGF), and soil fertility factor (SLPF) (Jones *et al.,* 2003).

Table 5. Selected soil parameters for the CSM-CROPGRO-Canola model from the experimental locations

Layer Depth (cm)	**Clay %**			**Silt %**			**Sand %**			**Bulk density (g cm^{-3})**		
	CHT	**STV**	**VYS**	**CHT**	**STV**	**VYS**	**CHT**	**STV**	**VYS**	**CHT**	**STV**	**VYS**
0-10	10.90	17.42	19.3	38.91	46.58	40.88	50.19	36.00	39.76	1.60	1.58	1.63
10-20	10.89	13.95	17.8	40.73	12.43	23.52	48.38	73.62	58.63	1.52	1.45	1.52
20-30	16.03	17.57	19.8	14.58	35.56	36.29	69.39	46.87	43.89	1.63	1.55	1.70
30-40	13.88	19.14	22.2	71.43	35.69	37.56	14.69	45.17	40.23	1.48	1.56	1.72
40-50	23.09	20.07	23.2	43.59	32.77	34.53	33.32	47.16	42.28	1.64	1.58	1.70
50-60	19.06	21.67	23.7	34.04	31.86	28.91	46.9	46.47	47.35	1.70	1.58	1.62

Layer Depth (cm)	**C_{org} (%)**			**pH in water**			**CEC (cmol kg^{-1})**		
	CHT	**STV**	**VYS**	**CHT**	**STV**	**VYS**	**CHT**	**STV**	**VYS**
0-10	2.47	1.65	1.81	7.88	6.85	7.09	21.05	18.11	18.74
10-20	2.36	1.64	1.78	7.61	6.40	6.71	21.23	18.02	18.88
20-30	2.24	1.61	1.76	7.85	6.29	6.91	20.96	18.11	19.86
30-40	2.55	2.05	2.91	7.97	6.81	7.52	20.96	17.93	19.78
40-50	2.49	2.04	2.22	8.18	7.10	7.69	20.96	17.48	18.92
50-60	2.46	2.00	2.16	8.22	7.03	7.18	20.87	17.57	17.92

Layer Depth (cm)	Total N (%)			LL ($cm^3\ cm^{-3}$)			DUL ($cm^3\ cm^{-3}$)		
	CHT	STV	VYS	CHT	STV	VYS	CHT	STV	VYS
0-10	0.13	0.09	0.10	0.25	0.18	0.19	0.36	0.32	0.33
10-20	0.10	0.12	0.13	0.25	0.17	0.18	0.35	0.33	0.34
20-30	0.11	0.11	0.12	0.25	0.17	0.19	0.36	0.31	0.34
30-40	0.14	0.09	0.10	0.26	0.19	0.21	0.36	0.28	0.31
40-50	0.13	0.09	0.10	0.26	0.19	0.20	0.34	0.29	0.31
50-60	0.11	0.11	0.11	0.26	0.18	0.18	0.35	0.34	0.35

*CHT-Chrastava; STV-Staňkov; VYS-Vysoká; Corg-organic carbon; CEC-cation exchange capacity; Total N-total nitrogen; LL-lower limit of available water to plant; DUL-drained upper limit or field capacity

Soil Water Index (SWI) for soil moisture balance

The Soil Water Index (SWI) quantifies the moisture status at different depths in the soil (equation 1). The amount of precipitation that infiltrates the soil through the infiltration process determines the soil moisture content. It is a very heterogeneous variable that is influenced, especially on a small scale, by soil properties and the type of drainage system (Herbert *et al.,* 2020). The SWI determination is as follows:

$$SWI(t_n) = \frac{\sum_i^n SSM(t_i) e^{\frac{t_n - t_i}{T}}}{\sum_i^n e^{\frac{t_n - t_i}{T}}} for\ t_i \leq\ t_n \qquad (1)$$

In the equation, t_n is the observation time of the current measurement, and t_i is the observation time of the previous measurements. Surface soil moisture (SSM) refers to the relative water content of the topsoil (up to a few centimeters), and it plays a significant role in the water and heat fluxes between the earth's surface and the atmosphere that control temperature and humidity (Montzka *et al.,* 2021). The health of the vegetation depends on the surface soil moisture, which is sensitive to environmental conditions like precipitation, temperature, and solar radiation. SSM thus serves as a key player in the global water, energy, and carbon cycles as well as an indicator of climatic conditions and a driver of regional weather and climate (Rasheed *et al.,* 2022).

3.4 Crop modelling activities

The Decision Support System for Agrotechnology Transfer (DSSAT) is a software application consisting of dynamic plant growth simulation models over 42 different crops (Fig. 5). DSSAT is supported by a variety of features and apps for meteorology, soils, genetics, crop management, experimental observational data, and sample datasets for all crop models. These simulation programs can model growth, development, and yield as a function of soil, plant, and atmospheric dynamics (Hoogenboom *et al.,* 2019a).

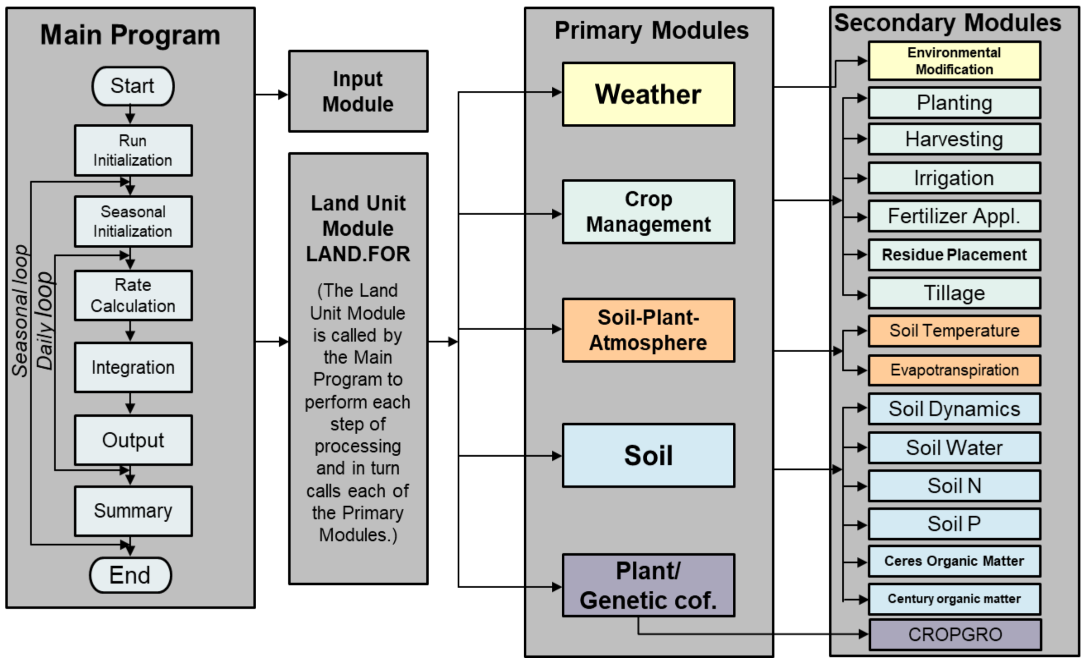

Figure 5. Main components and modular framework of DSSAT program

Oilseed crop model (CSM-CROPGRO-Canola) in DSSAT program

The CSM-CROPGRO model was developed as a genetic strategy for modeling to predict the growth and yield of different crops. Crop-specific ecotypes, species, and cultivar attributes are included in the model for simulating the growth and yield parameters based on the input dataset. Saseendran *et al.* (2010) first adapted the CSM-CROPGRO model based on the fava bean (*Vicia faba* L.) module to simulate canola parameters. Initially, N fixation issues were having problems simulating the proper nutrient management systems with the model. Later, using an experimental dataset of Mediterranean-grown soybeans (*Glycine max* L. Merr.), the nutrient management problem was solved utilizing model input data management (Deligios *et al.,* 2013). The CSM-CROPGRO model was adapted with the Decision Support System for Agrotechnology Transfer (DSSAT v4.6) to simulate crop parameters (Deligios *et al.,* 2013). The CSM-CROPGRO-Canola model in DSSAT is currently a useful tool for modeling canola growth and yield globally to evaluate crop responses to various environments, particularly under climate change (Jones *et al.,* 2003). The CSM-CROPGRO-Canola model was calibrated and evaluated using the observed data of Architect, Temptation, and Sněžka varieties from Chrastava, Staňkov, and Vysoká study locations. To successfully run the model, four types of data sets were used: 1. crop management data (e.g., land preparation, sowing, irrigation, fertilizer, phenological stages, harvest, yield, etc.); 2. weather data (e.g., experimental location-specific daily maximum and minimum air temperature (°C), total precipitation (mm), solar radiation ($MJm^{-2}day^{-1}$); 3. soil data (e.g., physical and chemical properties by layers); and 4. genetic data (e.g., variety-specific parameters, growth and development stages) (Fig. 6). Based on the input dataset, the CSM-CROPGRO-Canola model can simulate yields, biomass, leaf area index (LAI), and oiliness parameters for both current and projected climate conditions (Hoogenboom *et al.,* 2019b).

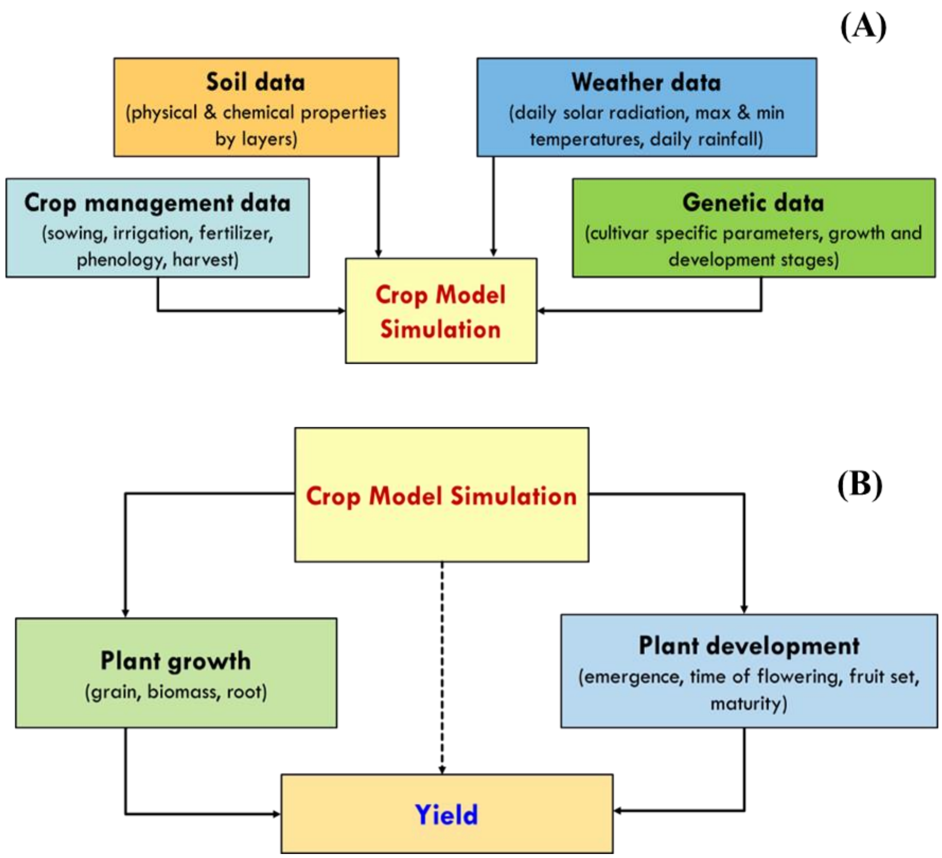

Figure 6. Simplified input (A) and output (B) components of CSM-CROPGRO model

Evaluation of crop simulation model

Crop model calibration is the process of comparing the observed and simulated values to confirm the acceptable estimates of the model outputs. Crop models require variety-specific genetic coefficients to simulate the performance of diverse genotypes under different soil, weather, and management conditions (crop growth, development, and grain production). The evaluation of the calibration outputs of different crop simulation models needs to operate in different ways. The performance statistic used in this study was the root mean square error (RMSE), which was calculated using equation (2). A lower RMSE value means smaller differences between simulated and observed values.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(\hat{Y}_i - Y_i\right)^2}{n}} \qquad (2)$$

where $\mathbf{Y_i}$ = observed value, $\mathbf{\hat{Y}_i}$ = simulated value, n = number of observations

4. RESULTS

The experimental results are based on the observation and evaluation of growth parameters in normal temperature and humidity conditions in 2020–2021 and in hot and alternating humidity conditions in 2021–2022. The sowing and wintering period in 2020–2021 in Chrastava took place under very warm and dry conditions, while the Staňkov and Vysoká locations had normal temperature and precipitation conditions. The beginning of flowering took place in Chrastava with cold and wet conditions, but for the Staňkov site, it was cold and dry. However, Vysoká had extremely cold and normal precipitation conditions. The phenological phase of seed formation took place in extremely warm and normal precipitation conditions for the Chrastava and Staňkov localities, while for Vysoká it was warm and very humid. In the case of seed maturity, Chrastava faced warm and very humid conditions; in Staňkov, the weather conditions were normal and slightly humid. In the case of the Vysoká location, the weather conditions were cold and slightly humid. In 2020–2021, both Vysoká and Staňkov locations experienced normal weather conditions for approximately 70% of the total growing season from September to March. In Chrastava, however, a greater fluctuation of weather was recorded, from slightly warm to strongly warm, with slightly cool and humid conditions. In the 2021–2022 growing season, moderate to strong heat prevailed at all three trial locations for approximately 50% of the total growing season. However, the precipitation conditions at the Chrastava site showed 60% of extreme events, when strongly dry conditions prevailed during the sowing, flowering, and maturity stages. While at the Staňkov and Vysoká locations, strongly dry conditions prevailed during the sowing and emergence periods, and slightly wet conditions during the maturity period.

4.1 Application of the CSM-CROPGRO-Canola model

Estimation of WOSR genetic coefficients

The crop management data from sowing to harvest (phenological and yield attributes) were organized from the experimental locations to prepare the genetic coefficients for all three selected varieties. The potential datasets required for genetic coefficient preparation for WOSR varieties in CSM-CROPGRO-Canola model are given in Table 6.

Table 6. Parameters finalization during the CSM-CROPGRO-Canola model calibration

Cultivar parameters	Definitions	Testing range	Calibrated values		
			Architect	Temptation	Sněžka
EM-FL	Time between plant emergence and flower appearance (R1) (photothermal days)	18-48	38.5	36.0	37.5
FL-SH	Time between first flower and first pod (R3) (photothermal days)	10-20	15.5	15.0	14.5
FL-SD	Time between first flower and first seed (R5) (photothermal days)	15-35	28.5	29.0	26.0
SD-PM	Time between first seed (R5) and physiological maturity (R7) (photothermal days)	20-38	28.5	27.0	25.5
FL-LF	Time between first flower (R1) and end of leaf expansion (photothermal days)	0.8-4.0	2.00	2.00	1.80
LFMAX	Maximum leaf photosynthesis rate at 30 °C, 350 ppm CO_2, and high light (mg $CO_2 m^{-2}$-s)	1-2.5	1.20	1.30	1.10
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm^2/g)	180-350	300	296	285
SIZLF	Maximum size of full leaf (three leaflets) (cm^2)	80-150	107.0	108.0	106.0
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell	0.8-1.5	1.00	1.00	1.00
WTPSD	Maximum weight per seed (g)	0.002-0.006	0.004	0.004	0.003
SFDUR	Seed filling duration for pod cohort at standard growth conditions (photothermal days)	15-28	20.0	20.0	20.0
SDPDV	Average seed per pod under standard growing conditions (#/pod)	12-25	21.0	22.0	20.0
PODUR	Time required for cultivar to reach final pod load under optimal conditions (photothermal days)	6-15	10.0	10.0	10.0
THRSH	The maximum ratio of (seed/(seed+shell)) at maturity. Causes seed to stop growing as their dry weights increase until shells are filled in a cohort. (Threshing percentage).	65-95	81.0	81.1	81.0
SDPRO	Fraction protein in seeds (g(protein)/g(seed))	0.15-0.28	0.240	0.242	0.235
SDLIP	Fraction oil in seeds (g(oil)/g(seed))	30-58	0.480	0.490	0.470
Ecotype parameters	**Definitions**	**Testing range**	**Calibrated values**		
			Architect	**Temptation**	**Sněžka**
PL-EM	Time between planting and emergence (V0) (thermal days)	1.2-5.8	3.80	3.72	3.61
EM-V1	Time required from emergence to first true leaf (V1), thermal days	3-10	6.7	6.0	6.1
V1-JU	Time required from first true leaf to end of juvenile phase, thermal days	0.0-0.8	0.6	0.4	0.5
JU-R0	Time required for floral induction, equal to the minimum number of days for floral induction under optimal temperature and daylengths, photothermal days	2-8	5.0	5.2	5.1
R7-R8	Time between physiological (R7) and harvest maturity (R8) (days)	2-18	9.0	10.0	8.5
RWDTH	Relative width of this ecotype in comparison to the standard width per node (YVSWH)	0.3-1.5	1.0	1.0	1.0
RHGHT	Relative height of this ecotype in comparison to the standard height per node (YVSHT)	0.5-2.5	1.2	1.0	1.0

Model assessment based on simulated and observed LAI

The comparison between simulated and observed LAI values provided insights into the reliability of the model in predicting LAI dynamics throughout the crop growing season 2020–2021 (Fig. 7). The agreement between the simulated and observed LAI values suggests that the CSM-CROPGRO-Canola model was successfully calibrated for accurately predicting LAI for the three WOSR varieties. The model performance statistics further support this conclusion, indicating the reliability of the simulated LAI values.

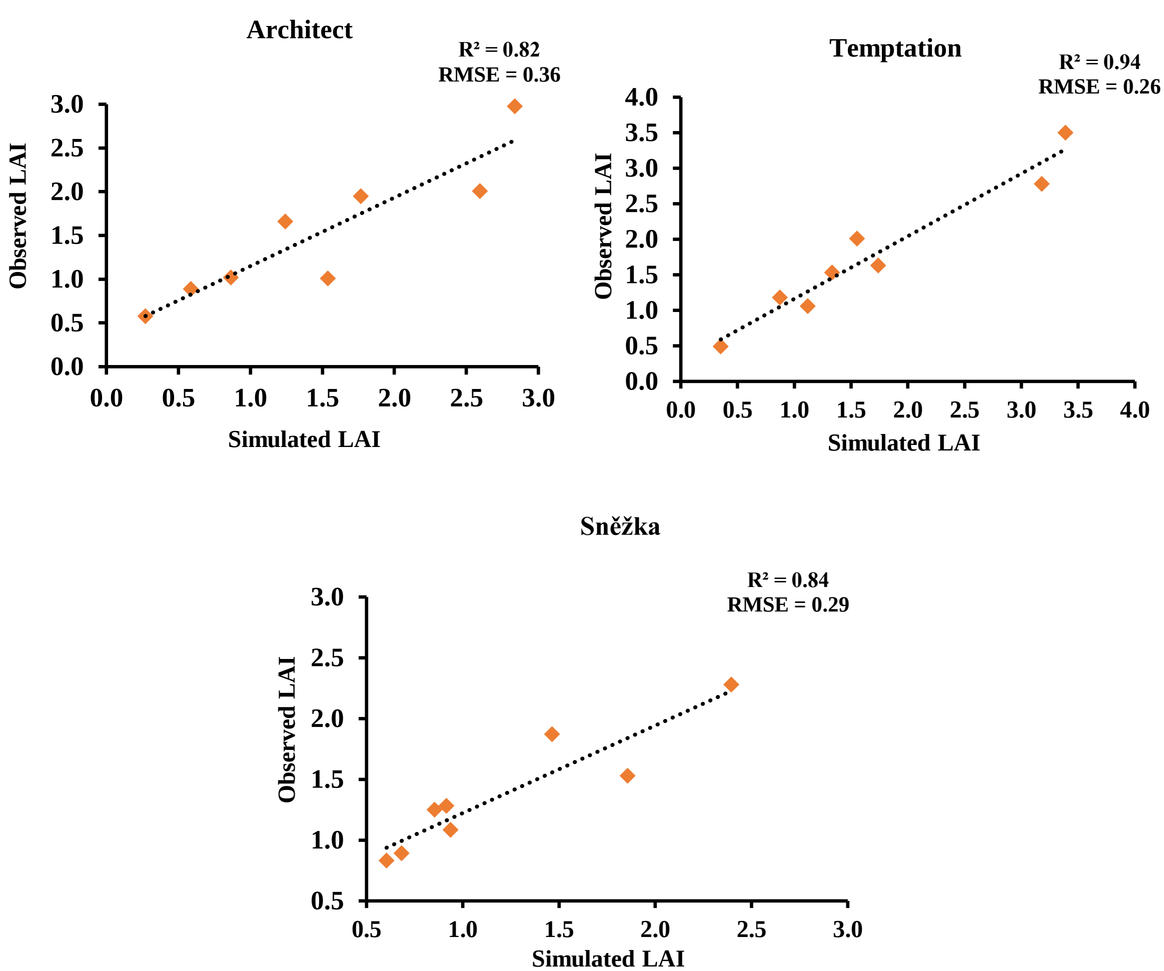

Figure 7. CSM-CROPGRO-Canola model assessment based on the observed and simulated leaf area index

The model calibration for the Architect variety performed well, with an R^2 value of 0.82 and an RMSE value of 0.36. These numbers showed low model prediction errors and a fair amount of correlation between the simulated and observed LAI values.

This suggested that the LAI dynamics of the Architect variety were accurately captured by the CSM-CROPGRO-Canola model throughout the growth season. The model calibration also demonstrated respectable performance statistics for the Temptation variety, with an R^2 value of 0.94 and an RMSE value of 0.26. The Temptation variety's simulated and observed LAI values showed a great connection and little mistakes, as demonstrated by the high R^2 and low RMSE values. Throughout the growing season, the LAI dynamics of this variety were precisely predicted by the CSM-CROPGRO-Canola model. With an R^2 value of 0.84 and an RMSE value of 0.29, the calibration of the Sněžka variety likewise showed a significant degree of agreement between simulated and observed LAI. These values also showed a strong correlation in the model predictions for the Sněžka variety.

The CSM-CROPGRO-Canola model accurately captured the LAI dynamics of this variety, suggesting its reliability in predicting LAI for the Sněžka variety during the growing season. However, in the case of the Architect and Sněžka varieties, the model underestimated LAI values only at the end of the vegetative phase, specifically during seed maturity. This might be attributed to certain factors that were not fully accounted for in the model, such as varietal-specific characteristics or environmental conditions during that particular phase. The comparison of simulated and observed LAI values for the three WOSR varieties suggested that the CSM-CROPGRO-Canola model performed well in accurately predicting LAI dynamics during the growing season. These results provide a valuable understanding of the growth and development of WOSR crops and can contribute to better management practices for optimizing crop yield and quality.

4.2 Model assessment based on simulated and observed seed yield and seed oil content

The CSM-CROPGRO-Canola model underestimated yields under normal weather conditions compared to the actual observed yields from all three locations for the Architect. The performance agreement between observed and simulated yields from the Chrastava location (RMSE = 0.26 t ha^{-1}) under normal weather conditions was used to calibrate the model for Architect. Under dry weather conditions, the model overestimated yields from Chrastava and Vysoká, while it underestimated yields at Staňkov.

For Temptation under normal weather conditions, the model showed good agreement in performance (RMSE = 0.04 t ha^{-1}) between observed and simulated yields at Chrastava. This performance result was used to calibrate the model for this variety. However, in dry weather conditions, the model overestimated simulated yields at all three locations. For Sněžka, the model overestimated yields compared to observed yields at Chrastava under normal weather conditions, but at Staňkov the model showed a good agreement of performance between simulated and observed yields (RMSE=0.07 t ha^{-1}), which was used to calibrate the model for this variety (Table 7). Under dry weather conditions, the model overestimated simulated yields at all three locations. Overall, model performance was variable across varieties and locations, and the model tended to overestimate yields under dry weather conditions rather than under normal weather conditions.

Table 7. Evaluation of the simulated CSM-CROPGRO-Canola model against observed seed yield

Experimental locations	**Variety**	**Year**	**Yields**
			RMSE (t ha^{-1})
Chrastava	Architect	2021	+0.80
		2022	-0.26
	Temptation	2021	+0.15
		2022	+0.04
	Sněžka	2021	+0.91
		2022	+0.35
Staňkov	Architect	2021	-0.18
		2022	-0.34
	Temptation	2021	+0.10
		2022	-0.38
	Sněžka	2021	+1.22
		2022	-0.07
Vysoká	Architect	2021	+0.93
		2022	-1.20
	Temptation	2021	+0.95
		2022	-0.59
	Sněžka	2021	+0.72
		2022	-1.29

The model consistently underestimated the seed oil content of all varieties from all locations under normal and dry weather conditions. For Architect, the model underestimated the simulated seed oil content at Chrastava, Staňkov, and Vysoká under normal weather conditions by 5.26%, 2.37%, and 1.18%, respectively. However, under dry weather conditions, the model underestimated the seed oil content by approximately 3% at all locations. Temptation at Vysoká showed a good agreement in performance between observed and simulated seed oil content (0.67%) under normal weather conditions. In contrast, at Staňkov and Chrastava, the simulated seed oil content was underestimated by the model between 3.36 % and 6.10 %. In dry weather, the model underestimated the seed oil content at Chrastava, Staňkov, and Vysoká by 4.21 %, 3.08 %, and 2.89 %, respectively. For Sněžka, the best agreement of model performance was evaluated at Vysoká under normal weather conditions, where the model underestimated the simulated seed oil content by 1.19% compared to the observed values. At the Staňkov and Chrastava locations, the model showed slightly higher deviations of 2.73 and 5.94%, respectively (Table 8). However, under dry weather conditions, the model underestimated the simulated seed oil content of all three experimental locations by a reasonably constant amount.

Table 8. Evaluation of the simulated CSM-CROPGRO-Canola model against observed seed oil content

Experimental locations	**Variety**	**Year**	**Seed oil content**
			RMSE (%)
Chrastava	Architect	2021	-3.15
		2022	-5.26
	Temptation	2021	-4.21
		2022	-6.10
	Sněžka	2021	-5.03
		2022	-5.94
Staňkov	Architect	2021	-2.85
		2022	-2.37
	Temptation	2021	-3.08
		2022	-3.36
	Sněžka	2021	-4.04
		2022	-2.73
Vysoká	Architect	2021	-2.21
		2022	-1.18
	Temptation	2021	-2.89
		2022	-0.67
	Sněžka	2021	-4.99
		2022	-1.19

4.3 Evaluation of simulated and observed yield and seed oil content of WOSR under different climatic conditions

Under the dry conditions (2020-2021), the observed yields for the Architect variety from Chrastava, Staňkov, and Vysoká locations were 4.26 t ha^{-1}, 4.51 t ha^{-1}, and 4.24 t ha^{-1}, respectively, while the simulated yields were 5.07 t ha^{-1}, 4.33 t ha^{-1}, and 5.17 t ha^{-1}, respectively. The observed yields for Temptation ranged from 3.85 t ha^{-1} to 5.84 t ha^{-1}, while simulated yields ranged from 4.47 t ha^{-1} to 5.94 t ha^{-1} at all experimental locations (Fig. 8). Moreover, the observed yields for the Sněžka variety were 4.17 t ha^{-1}, 4.41 t ha^{-1}, and 4.23 t ha^{-1}, while the simulated yields were 5.08 t ha^{-1}, 5.65 t ha^{-1}, and 4.95 t ha^{-1} (Fig. 8).

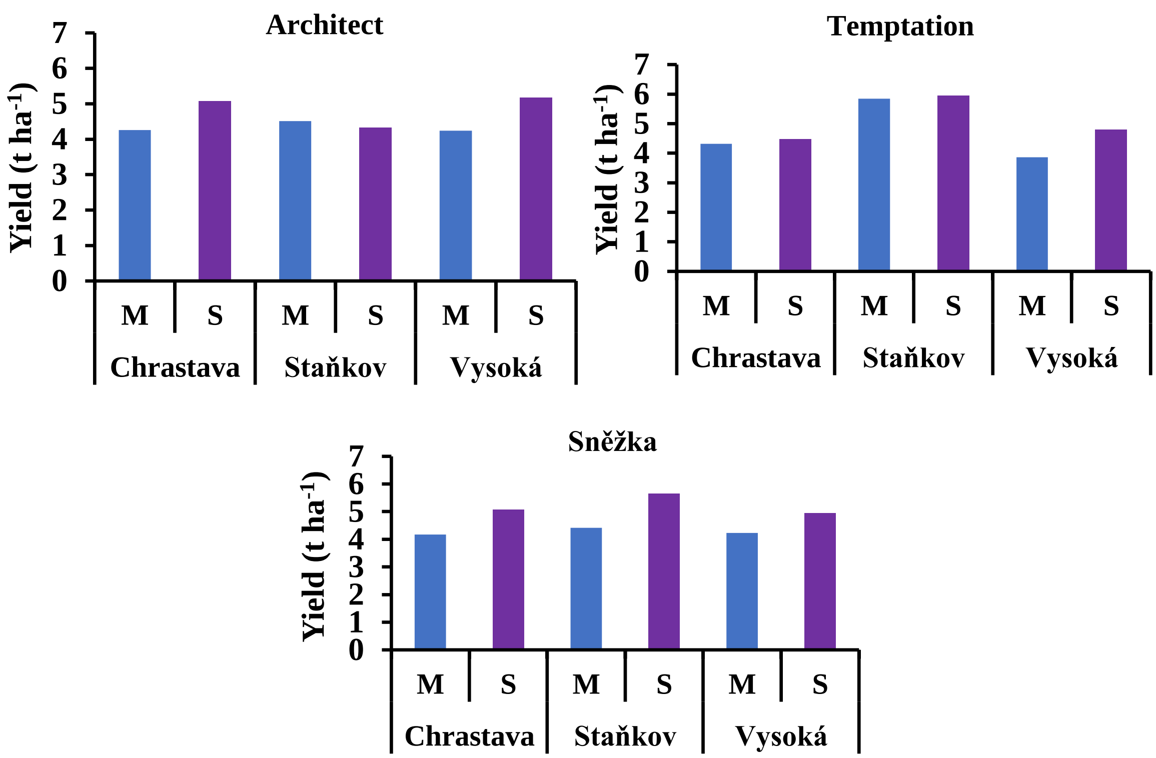

Figure 8. Observed and simulated yields of winter rape varieties for the 2020-2021 growing season. Yield is expressed as dry biomass per hectare (t ha^{-1})

Under normal weather conditions (2021-2022), the observed yields for the Architect variety from Chrastava, Staňkov, and Vysoká locations were 5.12 t ha^{-1}, 5.11 t ha^{-1}, and 6.15 t ha^{-1}, respectively, while the simulated yields were 4.86 t ha^{-1}, 4.77 t ha^{-1}, and 4.95 t ha^{-1}, respectively (Fig. 9).

The observed yields of Temptation ranged from 5.41 t ha^{-1} to 6.13 t ha^{-1} at all experimental locations, while simulated yields ranged from 5.03 t ha^{-1} to 5.63 t ha^{-1} at all experimental locations. Under normal weather conditions, the observed yields for the variety Sněžka were 4.40 t ha^{-1}, 4.93 t ha^{-1}, and 6.40 t ha^{-1}, while the simulated yields were 4.75 t ha^{-1}, 4.86 t ha^{-1}, and 5.10 t ha^{-1} (Fig. 9).

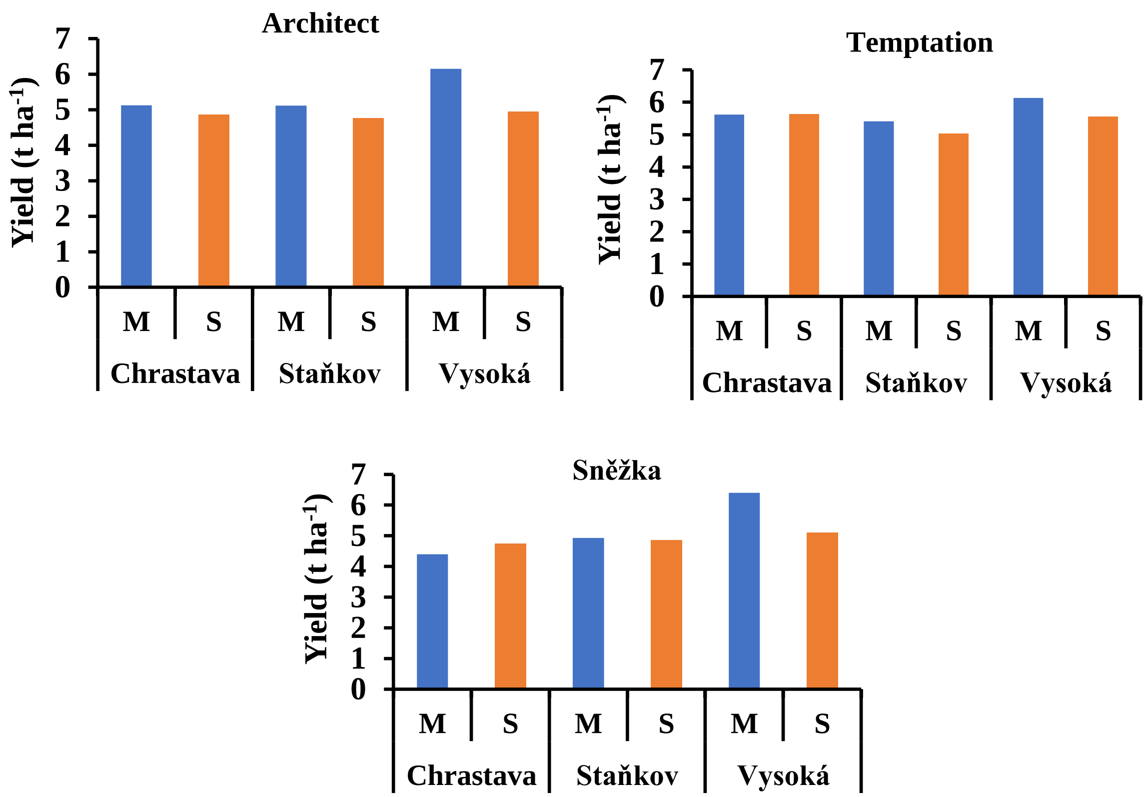

Figure 9. Observed and simulated yields of winter rape varieties for the 2021-2022 growing season. Yield is expressed as dry biomass per hectare (t ha^{-1})

Both observed and simulated yields were lower under drought compared to normal weather. However, in both years, the model underestimated simulated yields compared to the corresponding observed yields. In the case of seed oil content, under dry weather conditions, the observed oil content of Architect seeds from Chrastava, Staňkov, and Vysoká was 49.29%, 49.36%, and 48.18%, while the simulated seed oil content was 46.14%, 46.51%, and 45.97% (Fig. 10). Under normal conditions, the observed seed oil content ranged from 43.88 % to 48.84 % at all experimental locations, while the simulated seed oil content ranged from 43.58 % to 45.06 % at all experimental locations (Fig. 11).

For the Temptation variety, the observed seed oil content ranged from 48.30% to 51.31%, while the simulated seed oil content ranged from 45.41% to 47.10% at all experimental locations under dry conditions (Fig. 10).

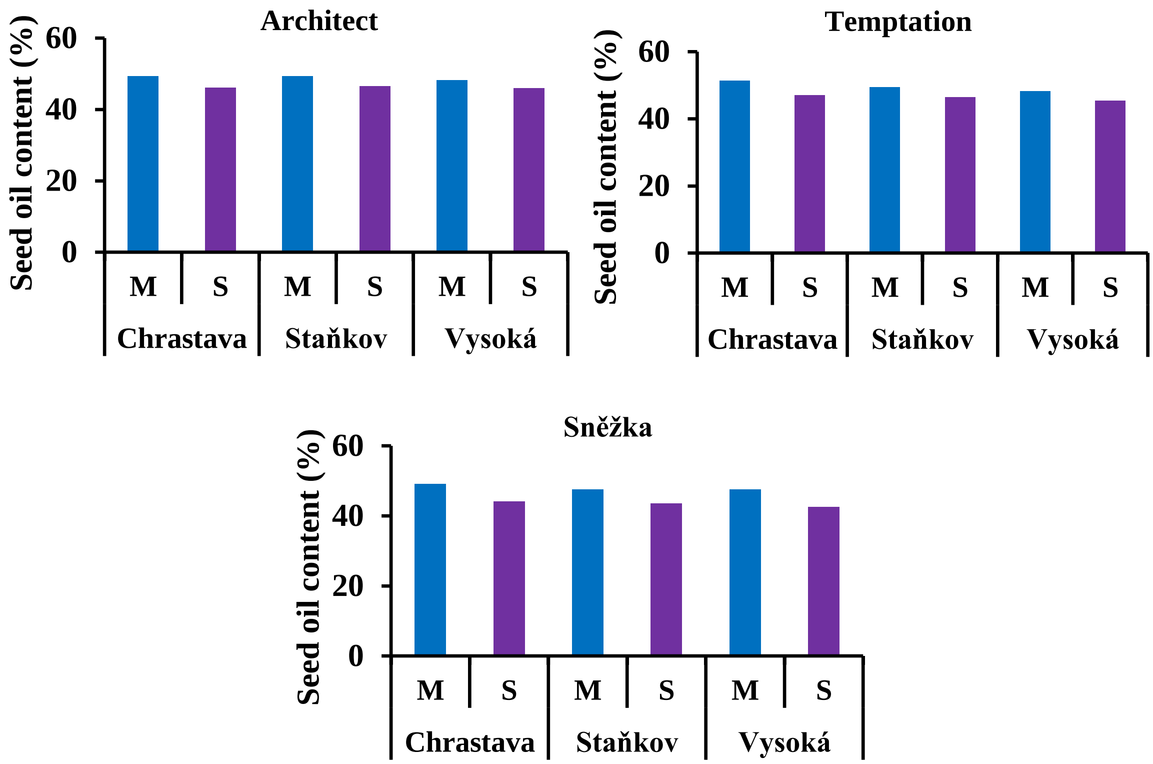

Figure 10. Observed and simulated seed oil contents of winter oilseed rape varieties for the 2020-2021 growing season

During normal conditions, the observed oil content of seeds of the variety Temptation from Chrastava, Staňkov, and Vysoká was 50.36%, 47.06%, and 44.80%, while the simulated oil content of seeds was 44.26%, 43.70%, and 45.47% (Fig. 11). Under dry weather conditions, the observed oil content of seeds of the variety Sněžka in Chrastava was 49.08%, 47.58%, and 47.52% in Staňkov and Vysoká, respectively, while the simulated seed oil contents were 44.05%, 43.54%, and 42.53%, respectively (Fig. 10). During the growing season 2021-2022, the observed seed oil contents were 48.08%, 44.78%, and 42.17%, respectively, while the simulated seed oil contents were 42.14%, 42.06%, and 43.36%, respectively (Fig. 11). However, the observed values for all varieties were relatively higher in the Vysoká location compared to the Chrastava and Staňkov locations.

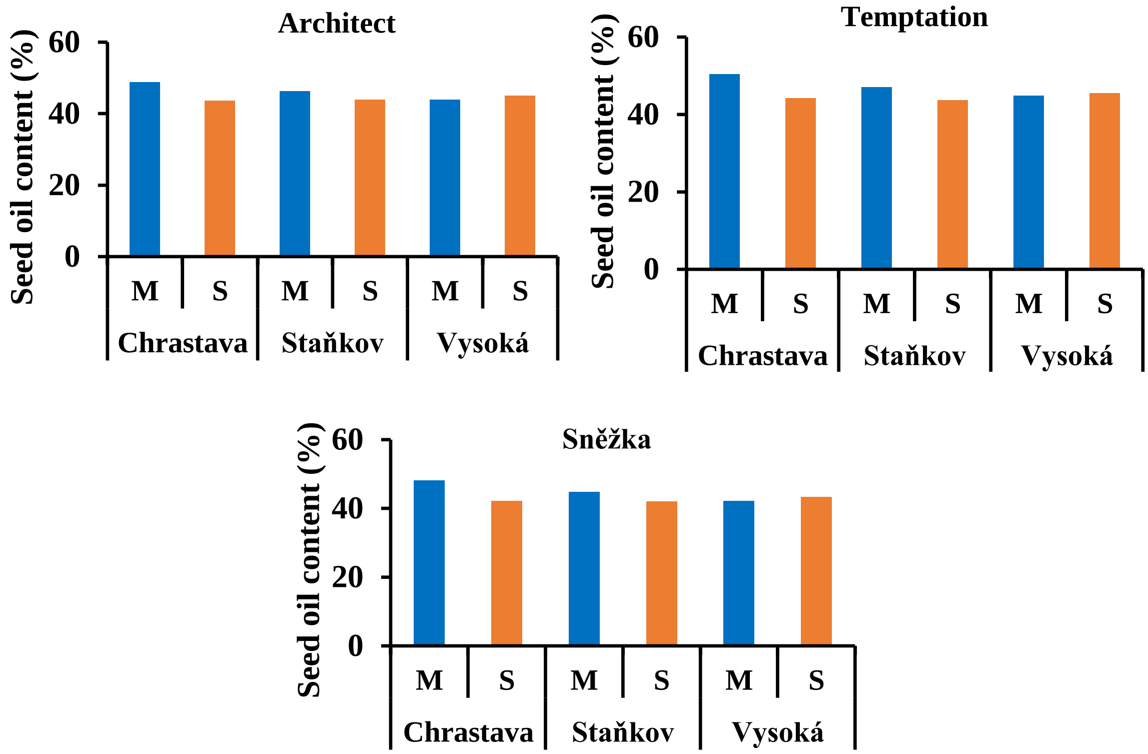

Figure 11. Observed and simulated seed oil contents of winter oilseed rape varieties for the 2021-2022 growing season

4.4 Risk of compound events to quantify the vulnerability of WOSR production

The results demonstrate that all three locations are sensitive to climate change impacts, and we anticipate significant changes in the occurrence of these compound events on WOSR. Three major events were analyzed here, namely, heat stress, black frost, and water logging conditions (Table 9). The findings reveal that climate change impacts are affecting all three locations, leading to notable changes in compound events under climate scenario RCP8.5 for the periods 2021–2040 and 2041–2060.

The occurrence of heat stress is expected to increase during both flowering and grain-filling periods in all regions. The most significant increase is assumed under the hot and humid scenario. Particularly, the Staňkov location experienced heat stress events during grain filling in 2015 and 2019. The analysis projected that heat stress during flowering remains minimal across all regions, while heat stress during grain filling is anticipated to rise significantly (Table 9). This increase varies from 27.69% in Chrastava to 46.15% in Staňkov.

The hot and wet scenario is expected to encounter an increasing number of heat stress occurrences, reaching 30% in Chrastava, 30.9% in Vysoká, and 49.6% in Staňkov by 2041–2060 (Table 10). Across the observation period, Vysoká had the lowest risk for heat stress during both flowering and grain-filling stages, while Staňkov demonstrated the highest risk for heat stress during flowering.

Among the compound events studied, the black frost occurrence demonstrates spatial and temporal variations. Mostly, the cold and dry conditions are associated with increased black frost events, while the hot and wet scenario leads to a decline. Examining meteorological data from 2010 to 2022, all three stations experienced black frost occurrences. Chrastava, for instance, recorded black frost for 7 days in 2011. Staňkov had occurrences in 2011, 2016, and 2020, each spanning 4 days. Vysoká observed black frost for 4 days in 2011 (Table 9). For black frost occurrences, Chrastava faces a risk of 30.77%, Staňkov 23.08%, and Vysoká 17.69%. While Chrastava might experience a slight increase to 30.9% by 2041–2060 under the hot and wet scenario, Staňkov could see a decrease of up to 19%. Conversely, the cold and dry scenario could raise black frost occurrences to 26%. Vysoká, under the hot and wet scenario, is projected to have a decrease of 13% by 2041–2060 (Table 10). During the observation period, Vysoká had the lowest risk for black frost, while Chrastava had the highest risk.

Table 9. Occurrence of compound risk events on WOSR for observation period 2010-2022 (cases/number of days)

Events (Chrastava)	Criteria	Growth stages	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Heat stress during flowering	Tmax> 35 °C at least for 2 days	Beginning to end of flowering	0	0	0	0	0	0	0	0	0	0	0	0	0
Heat stress during grain filling	Tmax >35 °C at least for 2 days	Flowering to maturity	0	0	0	0	0	0	0	0	0	0	0	0	1
Black frost	Tmin<-18 °C at least for 1 day + less than 1 cm of snow cover	Dormant season	1	7	0	1	0	0	1	0	0	0	0	0	0
Water logging during seeding and floral bud development	Soil moisture is at or above the filed capacity for more than 30 days from sowing to anthesis	Seedling and floral bud development	49	49	28	49	35	49	49	35	70	56	35	35	35

Events (Staňkov)	Criteria	Growth stages	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Heat stress during flowering	Tmax> 35 °C at least for 2 days	Beginning to end of flowering	0	0	0	0	0	0	0	0	0	0	0	0	0
Heat stress during grain filling	Tmax >35 °C at least for 2 days	Flowering to maturity	1	0	0	1	1	4	0	0	0	2	0	0	1
Black frost	Tmin<-18 °C at least for 1 day + less than 1 cm of snow cover	Dormant season	0	4	0	0	0	0	4	0	0	0	4	0	0
Water logging during seeding and floral bud development	Soil moisture is at or above the filed capacity for more than 30 days from sowing to anthesis	Seedling and floral bud development	42	42	21	35	28	42	35	35	49	56	35	28	28

Events (Vysoká)	Criteria	Growth stages	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Heat stress during flowering	Tmax> 35 °C at least for 2 days	Beginning to end of flowering	0	0	0	0	0	0	0	0	0	0	0	0	0
Heat stress during grain filling	Tmax >35 °C at least for 2 days	Flowering to maturity	0	0	0	0	0	1	0	0	0	0	0	0	0
Black frost	Tmin<-18 °C at least for 1 day + less than 1 cm of snow cover	Dormant season	0	4	0	0	0	0	0	0	0	0	0	0	0
Water logging during seeding and floral bud development	Soil moisture is at or above the filed capacity for more than 30 days from sowing to anthesis	Seedling and floral bud development	21	49	21	28	14	21	35	28	42	35	21	21	21

Water logging during seedling and floral bud development is expected to increase under the hot and wet scenario and decrease under the cold and dry scenario. Based on the meteorological data from 2010 to 2022, the occurrence of water logging is evident, with Chrastava experiencing the highest instances of high soil moisture content (99–100% SWI) during these stages (Table 9). This situation persisted for most of the observation period, indicating susceptibility to water logging. Staňkov and Vysoká had fewer occurrences. Concerning water logging events, the Chrastava location showed a high risk of about 32.31% during 2021–2040, but this concern is expected to decrease across all regions between 2041 and 2060. The cold and dry scenario indicates the most significant reduction, with Chrastava decreasing to 17% by 2041–2060. For Staňkov and Vysoká, the declines will be up to 12% and 4.5%, respectively (Table 10). Among the studied events, Vysoká had the lowest risk of water logging during seedling and floral bud development, while Chrastava had the highest risk. Converting the number of cases for each risk into percentages allows us to determine the relative frequency or risk of occurrence (Table 10).

Table 10. Projection of risk compound events occurrence on WOSR for the periods 2021-2040 and 2041-2060 under RCP8.5

Risk events	Risk of occurrence (%) for the observation period 2010-2022	RCP 8.5 (Chrastava)					
		2021-2040			2041-2060		
		MPI3	MPI1	MOHC2	MPI3	MPI1	MOHC2
Heat stress during flowering	0.0	0.5	0.0	0.5	0.75	0.0	1.5
Heat stress during grain filling	27.7	28.0	27.1	30.0	35.0	32.0	38.0
Black frost	30.8	31.0	33.0	30.9	30.0	36.0	28.0
Water logging during seeding and floral bud development	32.3	26.0	21.0	32.0	17.0	11.0	24.0
Risk events	Risk of occurrence (%) for the observation period 2010-2022	RCP 8.5 (Staňkov)					
		2021-2040			2041-2060		
		MPI3	MPI1	MOHC2	MPI3	MPI1	MOHC2
Heat stress during flowering	0.0	0.75	0.0	1.0	1.5	0.75	2.5
Heat stress during grain filling	46.1	47.0	46.0	49.5	53.0	51.5	55.0
Black frost	23.1	22.8	24.5	21.5	21.0	26.0	19.0
Water logging during seeding and floral bud development	24.2	20.0	16.0	23.0	12.0	8.0	17.0

Risk events	Risk of occurrence (%) for the observation period 2010-2022	RCP 8.5 (Vysoká)					
		2021-2040			2041-2060		
		MPI3	MPI1	MOHC2	MPI3	MPI1	MOHC2
Heat stress during flowering	0.0	0.0	0.0	0.7	1.0	0.5	1.5
Heat stress during grain filling	27.7	28.0	27.1	30.0	35.0	32.0	38.0
Black frost	17.7	17.0	19.0	16.5	15.5	22.0	13.0
Water logging during seeding and floral bud development	10.8	8.0	6.0	10.0	4.5	3.0	7.0

*MPI3- median (mean estimate) MPI1- cold and dry MOHC2- hot and wet

By analyzing meteorological data for the period 2010–2022, for Chrastava, Staňkov, and Vysoká stations, we determined the frequency of occurrence of different meteorological risk phenomena during that period (Fig. 12).

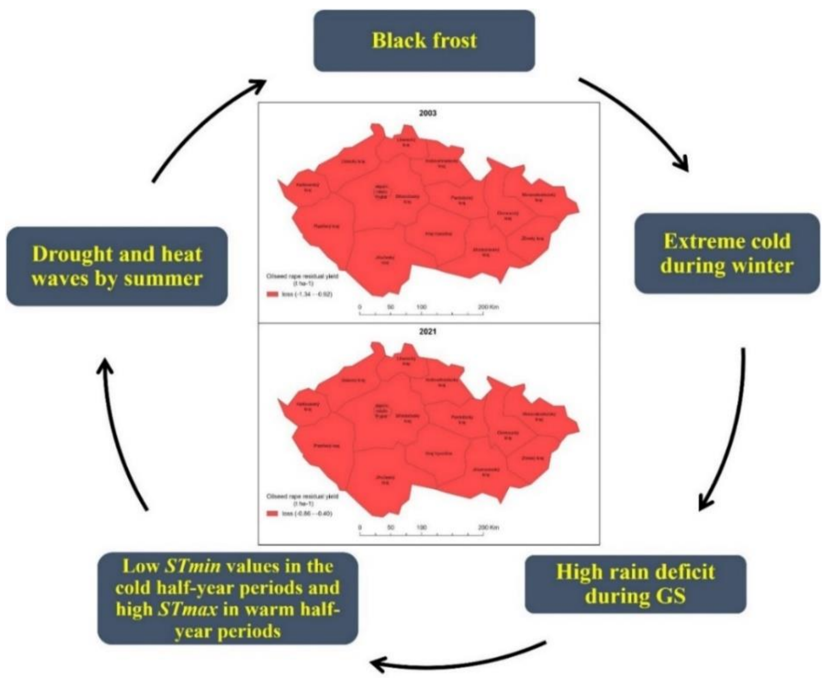

Figure 12. Compound events affecting yield attributes during WOSR growing season

Based on the impact assessment of the CEs, we also categorized the yearly yield performance of WOSR production with profit and loss during 2020–2021 in the Czech Republic using statistical indicators (Table 11).

Table 11. Impact assessment of compound events on WOSR using various statistical indicators (profit and loss) during 2000-2021 in the Czech Republic

Indicators (WOSR)	**Years**
Profit	2004, 2009, 2013, 2014, 2015, 2016
Loss	2002, 2003, 2011, 2012, 2017, 2019, 2020, 2021

The regression analysis of the residual yield outputs is presented as maps using the profit and loss assessment of the WOSR production from all regions of the Czech Republic to illustrate the annual agroclimatic drivers (Fig. 13).

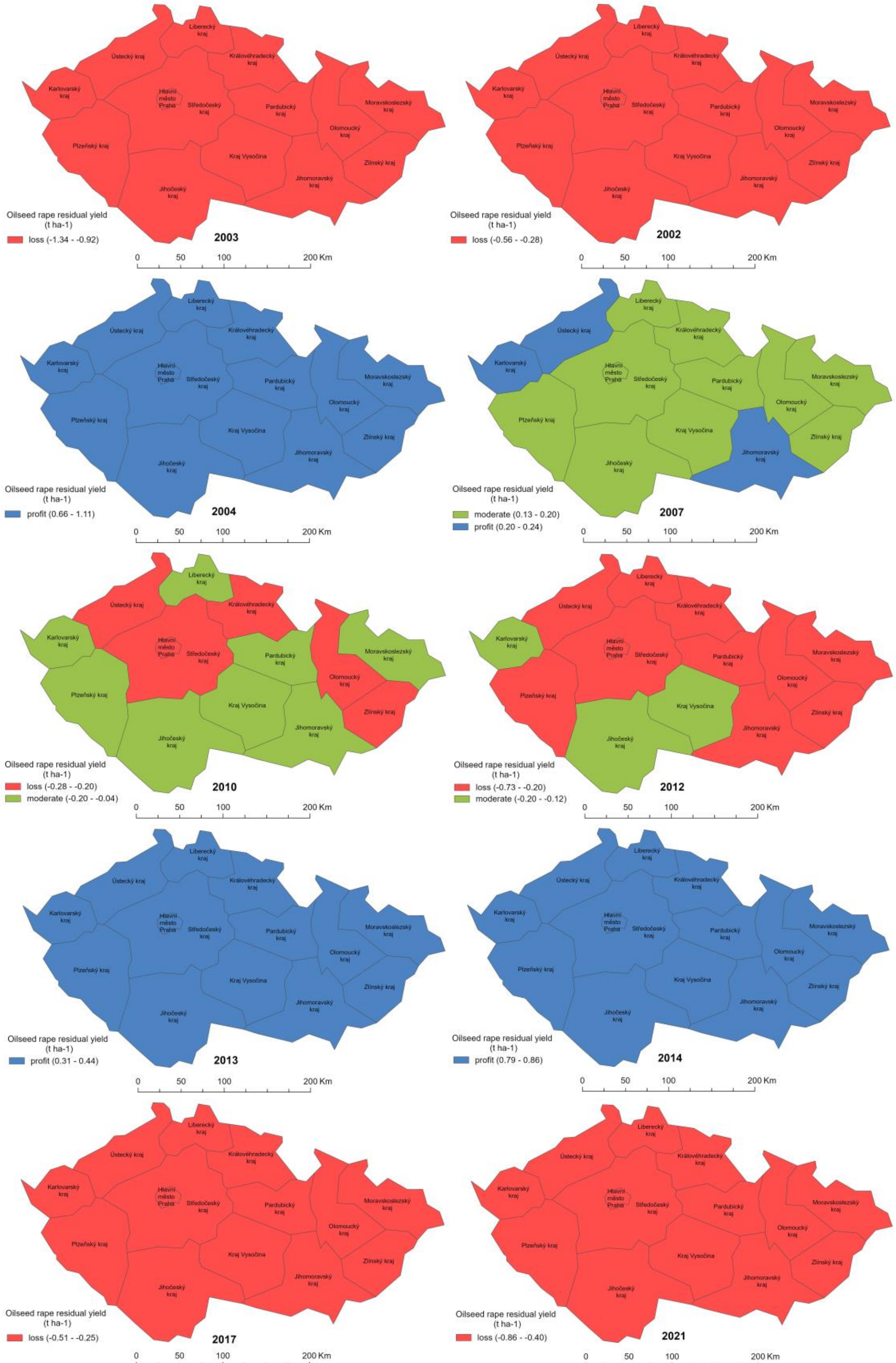

Figure 13. Compound events on residual yield performance of WOSR in the Czech Republic

4.5 Evaluation of WOSR varieties based on simulated yield attributes under current and projected climate scenarios

The DSSAT-CROPGRO model has an integrated "Environmental Module" that can be adjusted to projected climate changes such as air temperature, precipitation, and CO_2 concentration (Potopová *et al.,* 2023a). The study investigated the optimum growth and yield parameters for three winter rape varieties at three experimental locations under climate scenarios (Sc1) and (Sc2). The model simulated the highest maximum leaf area index (LAImax) for Temptation at all three experimental locations according to Sc1, while the Architect variety had the lowest LAImax. However, the Sněžka variety had the highest LAImax, and the Architect had the lowest LAImax under the Sc2 scenario. The Chrastava location showed the lowest LAImax, while the Vysoká location had the highest LAImax under both Sc1 and Sc2 scenarios (Fig. 14). Overall, the study showed that the varieties Temptation (Sc1) and Sněžka (Sc2) had the highest LAImax, while the variety Architect presented the lowest value in both scenarios. Under the conditions of scenario Sc1, the Temptation variety showed the highest simulated maximum LAI, ranging from 3.69 to 4.78 m^2 m^{-2} across all three experimental locations (Fig. 14). However, during Sc2, the Sněžka variety showed the highest simulated maximum LAI among all three varieties, ranging from 3.73 to 3.84 m^2 m^{-2}. The Architect variety showed the worst simulated maximum LAI according to Sc2 at the Chrastava location as 2.94 m^2 m^{-2}.

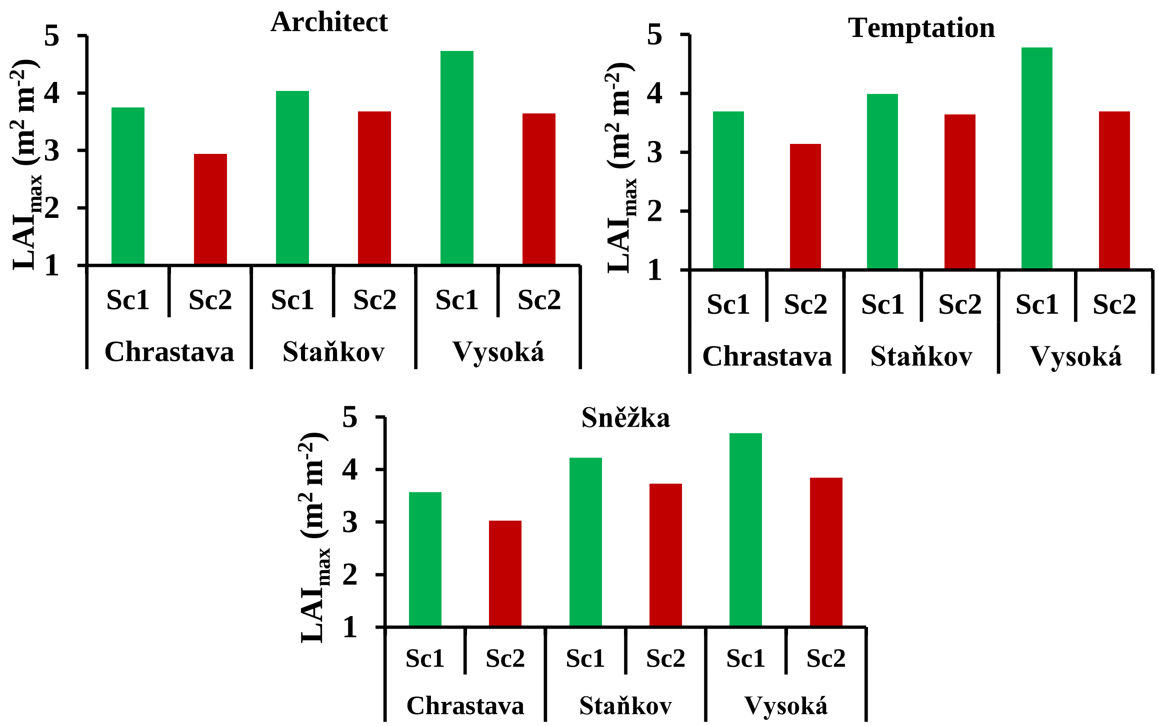

Figure 14. Simulated maximum leaf area index (LAImax) under current climate conditions for the field trials (Sc1) and the projected climate scenario (Sc2) for RCP8.5

Under scenario Sc1, the Temptation variety showed the highest simulated dry seed yields, ranging from 5.03 to 5.64 t ha^{-1} across all three experimental locations (Fig. 15). In contrast, the lowest simulated yield was found with the Architect variety. Under Sc2, the Sněžka variety performed the highest simulated yields among all three varieties, varying from 3.98 to 4.21 t ha^{-1}. The Architect variety showed the worst simulated seed yield according to Sc2 at the Chrastava location (3.88 t ha^{-1}).

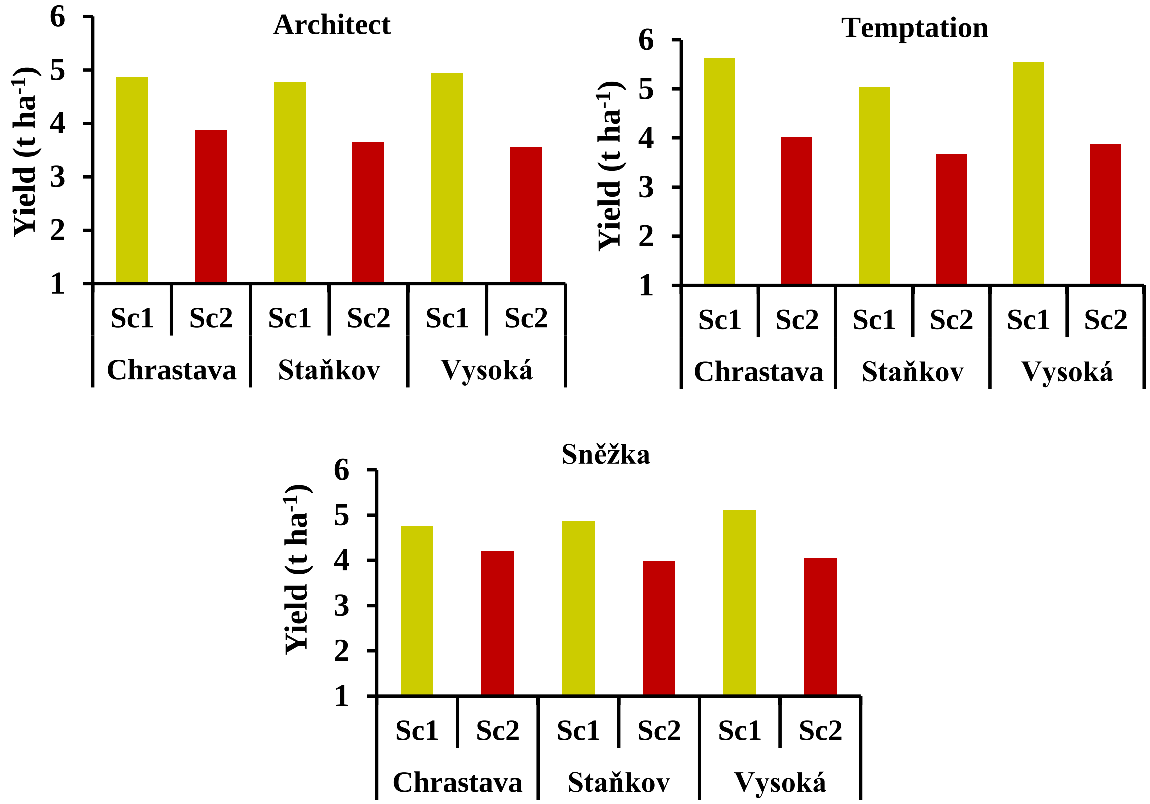

Figure 15. Simulated winter oilseed rape yields under current and future climate scenarios

Under scenario Sc1, the Temptation variety showed the highest simulated seed oil content, ranging from 43.70 to 45.47% in all experimental locations. Under Sc1, Sněžka and Architect varieties had intermediate seed oil content from 42.05 to 43.36% and 43.58 to 45.06%, respectively. However, under scenario Sc2, the highest seed oil content was 37.35 to 38.35% with the Temptation variety. However, Sněžka and Architect showed lower seed oil contents ranging from 36.21 to 37.27 and 35.93 to 36.69%, respectively (Fig. 16). The results also showed that the highest seed oil content was found at the Vysoká location, while the lowest seed oil content was found at Chrastava (Fig. 16).

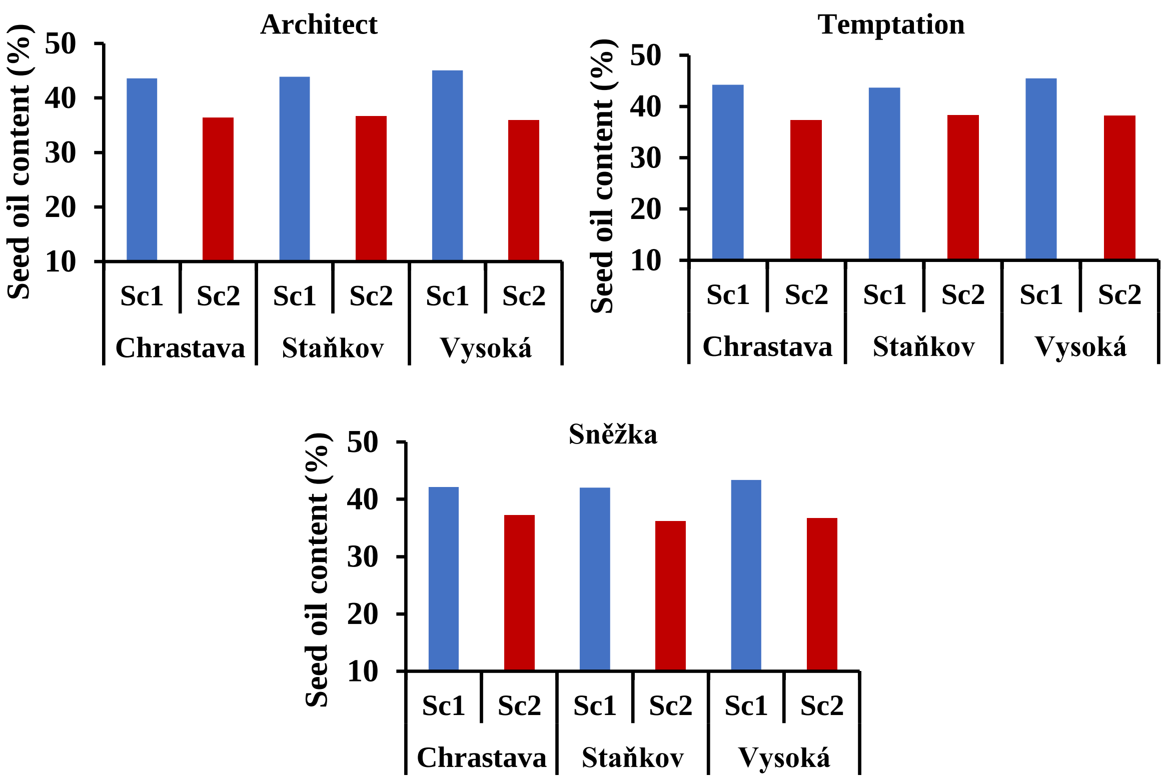

Figure 16. Simulated seed oil content under current and future climate scenarios

5. DISCUSSION

The CSM-CROPGRO model used in this study was tested and has been peer-reviewed in a scientific journal, which justified the validation and acceptance of the model used under the Czech Republic field conditions (Muntean *et al.,* 2021). Furthermore, the findings of the research were published as a practical, certified methodology approved by the Central Institute for Supervising and Testing in Agriculture under No. UKZUZ 106522/2023 (Potopová *et al.,* 2023b).

5.1 Implementation of the CSM-CROPGRO-Canola model

Uncertainty is considered a major concern when using crop growth models. During the calibration of the model, the most crucial step is to identify the optimization of errors by using specific objectives and approaches. This process involves a reliable understanding of the selected model's function (Ran *et al.*, 2022). Qian *et al.* (2018) found that the simulated yields of WOSR from various locations in Canada declined by 24 to 37.2% compared to the observed yields under RCP4.5 and RCP8.5, respectively. The yield reduction was mostly correlated with heat increases and water stresses under rainfed conditions, which were modelled using the CSM-CROPGRO-Canola model (DSSAT V4.6). Projected precipitation and CO_2 concentration were successfully addressed using the model based on future scenarios at global warming levels of 2.0 °C, 2.5 °C, and 3.0 °C, respectively (Qian *et al.,* 2019). Our results indicated that the CSM-CROPGRO-Canola model was successfully calibrated based on the input dataset and genetic coefficient of the WOSR variety. The performance agreement between observed and simulated yields for the Architect, Temptation, and Sněžka showed lower RMSEs of 0.26 t ha^{-1}, 0.04 t ha^{-1}, and 0.07 t ha^{-1}, respectively. In the case of seed oil content, the RMSE was 1.18%, 0.67%, and 1.19% for Architect, Temptation, and Sněžka, respectively. From these results, the accuracy of the model calibration and performance of the model were evaluated as a good fit for the simulation of selected WOSR varieties for experimental activities. The CSM-CROPGRO-Canola model was also successfully calibrated and evaluated in Wuhan, China, for nitrogen fertilizer doses and planting density experiments. The simulation results of the study showed significant accuracy with a small range of error of 0–3 days for the anthesis and a lower root mean square error (RMSE) of 7.48% for the yield attributes (Wang *et al.,* 2022).

5.2 Impacts of temperature changes

Temperature plays a vital role in crop growth and development, which in turn shapes crop phenological development and dry matter accumulation (Xiao and Tao, 2014). In many studies, it has been observed that crop yields are reduced due to prolonged seed-filling times due to early flowering and prolonged physiological maturation (Ahmad *et al.*, 2016; He *et al.*, 2016; Xiao *et al.*, 2013). Temperature played a crucial role in determining the timing and duration of key phenological stages in winter oilseed rape. The phenological development of WOSR is regulated by temperature, vernalization (cold exposure is essential for flowering), and the photoperiod from leaf initiation to stem elongation (Böttcher *et al.,* 2016). Poor stem establishment before winter can result in remarkable foliage loss, a reduced leaf area index, and declining nitrogen storage due to low temperatures and low light intensity during winter (Bhattacharya, 2022). However, increased temperatures and prolonged day lengths delayed the vernalization period (Hoffmann *et al.,* 2015). When temperatures remain above 0°C continuously, WOSR experiences rapid growth and produces most of its aboveground biomass over a few weeks. The most favorable temperatures for photosynthesis, vegetative growth, and reproductive processes range from 21 to 25°C (Deligios *et al.,* 2013). Warmer temperatures during the vernalization period resulted in enhanced crop vegetative development (Korres *et al.,* 2016). A higher temperature during flowering was found to cause a decrease in seed set and seed weight, ultimately reducing the crop's yield potential (Wu *et al.*, 2020).

Temperate climates reduce growth periods by approximately 1°C of increase in ambient temperature (Joy *et al.*, 2020). Conversely, optimum seed and oil yield production needs specific day/night average temperature ranges around 20 to 15°C and 15 to 13°C, respectively (Marjanović-Jeromela *et al.*, 2019). Late sowing dates also significantly reduce primary branches and flowers per plant (Balodis and Gaile, 2016). High temperatures reduced the length of seed development inside the pods and may have enhanced the senescence of leaves to *reduce* photosynthetic capacity (Weymann *et al.*, 2015). In our study, we found that the growth and development of WOSR showed the effects of temperature changes.

Based on the results and the weather evaluation, the warm temperature region Chrastava has lower growth and a lower leaf area index (LAI) of 3.75, 3.69, and 3.57 $m^2 m^{-2}$ for Architect, Temptation, and Sněžka, respectively. However, the normal temperature region Vysoká showed higher growth and LAI ranges from 4.73, 4.78, and 4.69 $m^2 m^{-2}$ for Architect, Temptation, and Sněžka, respectively. In the case of the projected temperature scenario, the highest simulated maximum LAI was recorded from the Vysoká location with the Sněžka variety, while the Chrastava location showed the worst simulated maximum Lai with the Architect variety.

5.3 Impacts of drought stress

Extreme droughts and water scarcity can lead to various environmental issues, including poor crop establishment and decreased crop yields (Chen and Sun, 2015; Lobell *et al.,* 2011). Several climate factors play a role in the occurrence of droughts and affect crop production (Wang, 2017; Chen *et al.*, 2013; Trnka *et al.*, 2011). The initial effect of drought on plants is poor germination and damage to seedling establishment. Various studies have reported the negative effects of drought stress on germination and seedling growth (Marthandan *et al.*, 2020). Drought impacts the quantity and size of individual leaves. Generally, leaf expansion is dependent on turgor pressure and assimilation. Reduced turgor pressure and slowed photosynthesis under dry conditions are the main limiters of leaf expansion (Hageman and Van Volkenburgh, 2021). Fresh and dry weights are also significantly reduced under low water conditions (Zhao *et al.,* 2022; Potopová *et al.*, 2018).

Plant growth occurs primarily through cell division, proliferation, and differentiation. Drought impairs mitosis and cell expansion, resulting in poor growth (Koch *et al.,* 2019). Drought limits cell growth primarily due to the loss of turgor (Begna, 2020). Low-water conditions lead to impaired cell elongation, mainly due to poor water movement from the xylem to neighboring cells (Wahab *et al.,* 2022). In our study, 2020–2021 was found to be a dry growing season with severe dry days during crop establishment in comparison with the growing season 2021–2022, based on the weather evaluation. Dry weather conditions during early crop establishment and growth have effects on WOAR yields. Substantial yield variations have been observed between the dry and normal growing seasons.

Under normal conditions, the observed yields vary from 4.40 to 6.40 t ha^{-1}, whereas under dry conditions, the yield ranges from 3.86 to 5.84 t ha^{-1}. Studies by Weymaan *et al.* (2015) suggest that drought stress before flowering can primarily decline total biomass production. However, a lack of water during flowering reduces total pod density. In addition, the limited-water condition between anthesis and maturity impacts the seed weight and seed oil concentration.

5.4 Risk assessment of compound events during WOSR production

Compound events in central Europe, including the Czech Republic, can manifest in various ways, and their impacts on WOSR can be more severe than single events in isolation. For instance, the simultaneous occurrence of heatwaves and droughts can lead to water stress and reduced photosynthesis, negatively affecting crop yield (Rivero *et al.*, 2022; Potopová *et al.*, 2021a–b). In contrast, floods during the germination and flowering stages can cause waterlogging that can lead to root damage and reduced nutrient uptake, lowering the yield potential of WOSR (Shahzad *et al.*, 2021). Also, compound events can amplify the risks of pest and disease outbreaks due to changes in temperature and moisture availability, compromising crop health (Challinor *et al.*, 2018). Compound events on WOSR in the Czech Republic can arise from the simultaneous occurrence of heatwaves, droughts, heavy precipitation, and frost events. The interaction of these events leads to increased stress levels for the crop, affecting growth, development, and yield. Prolonged heat waves during flowering stages can reduce pollen viability and limit successful pollination, leading to poor seed set and yield losses (Chen *et al.*, 2021). Additionally, combinations of water deficits and extreme heat can induce moisture stress, further hindering WOSR productivity (Rivelli *et al.*, 2023).

Various studies have demonstrated that the Czech Republic has seen an increase in the frequency and magnitude of compound events in recent decades. The region witnessed more prolonged heatwaves and concurrent dry spells, especially during the critical growth stages of WOSR, leading to significant yield reductions (Reddy, 2015). Also, extreme precipitation events became more common, resulting in soil waterlogging and increased runoff, impacting the crop's development and nutrient absorption (Zscheischler *et al.*, 2020).

Changing climate patterns are primarily attributed to gas emissions, especially greenhouse gases from human activities, leading to global warming and alterations in atmospheric circulation patterns. All these changes intensify the likelihood of compound events occurring in Central Europe, including the Czech Republic, that can lead to more frequent and severe impacts on WOSR and other oilseed crops (IPCC, 2014).

In the growing season 2021–2022, the observed phenological phases (first pod, seed, maturity) showed an optimal length of growth phases, while in the growing season 2020–2021, extreme weather events shortened the phenological phases. Thus, the results showed that all measured values of the individual phenological phases identified higher values in the colder area (Vysoká) and lower values in the warmer area (Chrastava). In the case of initial pod formation, the simulated values under normal weather conditions in 2021–2022 were overestimated by the model by 15.13 to 20.96%. However, for hot and dry weather in 2020–2021, the model underestimated the values by 11.74 to 22.69%. The simulated days of first seed formation were underestimated by 9.92 to 16.60% for both years. In addition, the model underestimated the values of physiological maturity from 6.95 to 22.14% and harvest maturity from 7.54 to 20.80%, respectively, in all locations and years. The slight deviation in the simulated and experimental values may be due to the inability of the crop model to capture the controlled experimental conditions at the CISTA experimental stations.

Study conducted by Hájková *et al.,* (2021) examined the impact of temperature and precipitation on the phenological stages and yield components of winter oilseed rape cultivars. The study emphasized the impact of temperature in determining the oil content of WOSR. Warmer temperatures were associated with lower oil content, potentially impacting the quality and economic value of the crop. During seed development, temperature and precipitation substantially affect yield by influencing the assimilation duration and rate of seed filling (Sehgal *et al.,* 2018). Yield potential may be determined until the end of flowering, but its consciousness mostly depends on temperature and water availability during subsequent growth phases (Weymann *et al.,* 2015). Rising temperatures result in more frequent droughts and decreased crop productivity (Liu *et al.,* 2016). Moreover, lower solar radiation can also negatively impact crop yields (Yang *et al.,* 2019).

5.5 Uncertainty in climate scenarios (temperature and precipitation) for the Czech Republic

In the Czech Republic, the 21st century promises a profound transformation in climate conditions, marked by significant shifts in both temperature and precipitation patterns. These projections, drawn from multiple climate experiments and scenarios, reveal an alarming trajectory of the climate for the region (Zahradníček *et al.,* 2016). Depending on the emissions scenario, the annual temperature is poised to increase substantially. Under the RCP4.5 scenario, a yearly rise of 2.0 °C is expected towards the end of this century, compared to the reference period between 1981 to 2010 (Zahradníček *et al.,* 2016). However, the more severe RCP8.5 scenario shows an even grimmer picture with a doubling of the temperature increase to 4.1 °C annually within the same timeframe (Zandvoort *et al.,* 2017). Holtanova *et al.,* (2014) found that the climate situation becomes increasingly unpredictable beyond 2050 for the Czech Republic, with deviation among emissions scenarios. Under the RCP8.5 scenario, temperatures variations might act dramatically, with projecting an incredible 5 °C increase by the end of the century compared to the reference period of 1981-2010 (Potopová, *et al.,* 2018). In contrast, the RCP4.5 scenario showed a relatively stable climate from 2061 onward, with temperatures rising by approximately 2°C (Jevšenak *et al.,* 2021).

In relation to rising temperatures, precipitation patterns are undergoing transformation with high spatial and temporal variability (Santos *et al.,* 2010). Projections from Euro-CORDEX experiments indicate a modest increase of approximately 7–13% in precipitation sums under RCP4.5 and 6–16% under RCP8.5 by the end of the century (Mihai *et al.,* 2022). However, the variability in precipitation is contingent upon factors such as atmospheric circulation and the nation's intricate topography. Despite these forecasts of slightly increased precipitation, a growing concern is the rise in evapotranspiration due to elevated temperatures and shifting precipitation patterns, potentially favoring drought conditions in the future (Madsen *et al.,* 2014). Drought is a rapidly increasing issue in the Czech Republic, with recent years witnessing a surge in occurrences, including droughts in 2012, 2013, 2014, and 2015 (Acosta *et al.,* 2020).

These droughts stem from a combination of below-average precipitation and remarkably high temperatures. Unexpectedly, while the new Euro-CORDEX experiments project slightly higher precipitation sums, the synergy of increased temperatures and altered precipitation frequencies may aggravate evapotranspiration, further intensifying the risk of drought in the coming years Particularly, the climate impact extends to temperature extremes, with prolonged heatwaves emerging as a significant concern (Berg *et al.*, 2019). Moreover, heatwaves have the potential to compound drought conditions, increase evapotranspiration, and accelerate landscape desiccation (Rulfová *et al.,* 2017).

6. CONCLUSIONS

Winter oilseed rape is the EU's dominant oil crop for food and feed purposes. Compound climate events are now an alert concern for farmers, researchers, and policymakers to achieve sustainable crop production with increasing demand. The current findings highlight the performance of three winter oilseed rape varieties, Temptation, Architect, and Sněžka, at three different experimental locations under current climate conditions and projected simulation conditions for future scenarios. The simulation model CSM-CROPGRO-Canola was tested for the first time in the Czech Republic. The study also evaluated the yield performance of the varieties using the CSM-CROPGRO-Canola simulation model based on the weather conditions and plant-soil-atmosphere dynamics. The practical application of this crop model was found to be realistic when modelling the suitability of varieties for different agroclimatic conditions based on the results obtained through this study. The summary of the results from the current study is:

- The research confirms the first hypothesis that the intensity and frequency of compound weather events will negatively impact the quantity and quality of winter oilseed rape (WOSR) crops. Under the present climatic conditions, the Staňkov region experienced more pronounced heat stress during the flowering and grain-filling stages. Moreover, the study predicts that in the future, the Staňkov region will face a greater likelihood of heat stress compared to the Chrastava and Vysoká regions. Nevertheless, the possibility of water logging during seedling and floral bud development will decrease across all three locations, indicating an increased probability of drought occurrences. In terms of black frost events, the cold and dry scenario could lead to reduced yields in all three areas, with the highest risk observed in the Chrastava region.
- The study also validated the second hypothesis that fluctuations in temperature impact the growth and development of WOSR due to climate change. Evaluating the agrometeorological conditions, we observed that the warmer region of Chrastava showed reduced plant growth and a lower Leaf Area Index (LAI) compared to the colder Vysoká region. Furthermore, the simulated LAI and yield attributes showed lower values under the projected temperature scenario of +2°C (Sc2) than the current temperature condition (Sc1), regardless of the variety and location.

- The current research further validates and confirms the third hypothesis by comparing the two distinct growing seasons: 2021–2022, considered normal weather conditions, and 2020–2021, the dry season. When comparing the agrometeorological conditions of these two growing seasons, it became clear that the dry season hampered the early establishment of crops, causing insufficient crop growth and ultimately leading to a decrease in crop yield. Significant yield variations have been observed across experimental regions. In normal agrometeorological conditions, the range for the lowest and highest yields was 4.40 to 6.40 t ha^{-1}, while during the dry growing season, this range was 3.86 to 5.84 t ha^{-1}, respectively.
- The study confirms the final hypothesis regarding the joint precipitation and temperature extremes during the seed-filling stage. The model's yield estimations under normal weather conditions in the 2021–2022 growing season were found to be higher than observed values, surpassing them by 15.13% to 20.96%. However, during the hot and dry weather of the 2020–2021 season, the model underestimated the yield values by 11.74% to 22.69%, illustrating the impacts of simultaneous precipitation and temperature events. Furthermore, under the conditions of hot and dry weather, the model's estimations for physiological maturity were lower than the observed values by 6.95% to 22.14%, and for harvest maturity, the underestimation ranged from 7.54% to 20.80%.

To sum up, this doctoral dissertation successfully addressed all the hypotheses and fulfilled the objectives. Our findings assume that the Sněžka variety consistently displayed the highest seed yield across all three locations under both present and projected climate scenarios, whereas the Temptation variety exhibited the highest seed oil content among the tested WOSR varieties. While considering the compound weather events across the experimental locations, the Vysoká and the Chrastava areas exhibited the greatest and the lowest seed yield, respectively. On the other hand, it is found that the Sněžka and Temptation varieties have the potential to achieve higher seed and oil yields under climate change conditions. As a part of further research, the DSSAT Foundation from the United States would like to incorporate our experimental data and crop simulation results of these new varieties of winter oilseed rape into their global DSSAT database for the upcoming version of the program.

7. PUBLICATIONS AND OUTCOMES

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Article

Climate Change Impacts Assessment Using Crop Simulation Model Intercomparison Approach in Northern Indo-Gangetic Basin of Bangladesh

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Abstract: The climate change impacts of South Asia (SA) are inextricably linked with increased monsoon variability and a clearly deteriorating trend with more frequent deficit monsoons. One of the most climate-vulnerable nations in the eastern and central Indo-Gangetic Basin is Bangladesh. There have been numerous studies on the effects of climate change in Bangladesh; however, most of them tended to just look at a small fraction of the impact elements or were climatic projections without accounting for the effects on agriculture. Additionally, simulation studies using the CERES-Rice and CERES-Wheat models were conducted for rice and wheat to evaluate the effects of climate change on Bangladeshi agriculture. However, up to now, Bangladesh has not implemented farming system ideas by integrating cropping systems with other income-generating activities. This study was conducted as part of the Indo-Gangetic Basin (IGB) regional evaluations using the protocols and integrated assessment processes of the Agricultural Model Intercomparison and Improvement Project (AgMIP). It was also done to calibrate crop models (APSIM and DSSAT) using rice and wheat. To assist policymakers in creating national and regional plans for anticipated future agricultural systems, our work on the integrated evaluation of climate change impacts on agricultural systems produced realistic predictions. The outcome of this research prescribes a holistic assessment of climate change on future production systems by including all the relevant enterprises in the agriculture sector. The findings of the study suggested two major strategies to minimize the yield and increase the profitability in a rice–wheat cropping system. Using a short-term HYV (High Yielding Variety) of rice can shift the sowing time of wheat by 7 days in advance compared to the traditional sowing days of mid-November. In addition, increasing the irrigation amount by 50 mm for wheat showed a better yield by 1.5–32.2% in different scenarios. These climate change adaptation measures could increase the per capita income by as high as 3.6% on the farm level.

Keywords: APSIM and DSSAT crop simulation models; climate change impact; cropping system; Indo-Gangetic Basin (IGB); integrated approach

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1. Introduction

Climate change impacts are increasingly visible in South Asia (SA), with greater variability of the monsoon, noticeably, a declining trend with more frequent deficit monsoons [1]. Bangladesh is one of the most climate-vulnerable countries in the central and eastern Indo-Gangetic Basin. The rapidly growing population of the country puts tremendous pressure on its scarce natural resources. The country is vulnerable to many climatic

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The ability of CROPGRO-Tomato model to simulate the growth characteristics of Thomas F1 tomato cultivar grown under open field conditions

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Abstract

There are few studies about the ability of CROPGRO-Tomato model to simulate tomato growth under field conditions as a function of both local weather and soil conditions. The aim of this work was to calibrate the CROPGRO-Tomato model, included in the Decision Support System for Agrotechnology Transfer (DSSAT) software, for the Thomas F1 indeterminate tomato cultivar grown under open field conditions at two locations in the Czech Republic with different soil and climate conditions. Additionally, this paper focuses on modelling the impact of compound weather events (CEs) on the growth characteristics of the hybrid field tomato variety. The genotype file, including the main parameters of crop phenology and plant growth, was adapted to the Thomas F1 indeterminate tomato cultivar. The CROPGRO-Tomato model was calibrated by inputting the soil characteristics, weather data and crop management data and then by adjusting the genetic coefficients to simulate the observed Leaf Area Index (LAI) and Above Ground Biomass (AGB) from transplanting to harvest under the farmers' field conditions. The comparison of the LAI simulated by the model and measured under field conditions showed adequate representation with the root mean square error of 0.86 and 1.11 m^2/m^2. Although there was a good fit for LAI and AGB between the simulated and measured data during the first part of the growing season, increasing differences were found in the growing season with cool-wet and/or hot-dry thresholds of CEs.

Introduction

Field-grown tomatoes are exposed to an assortment of extreme weather events and climate conditions, but the impacts of such factors are complex and difficult to assess. Fruit formation in tomato cultivars decreases when temperatures are too high and drought frequency increases (Potopová *et al.*, 2017*a*). The combination of multiple weather and climate events is considered to be a compound event (CEs) and results from a combination of climatic variables (extreme precipitation and wind, heatwaves and drought, heatwaves and violent storms) (Zscheischler *et al.*, 2017). Thus, CEs have a huge impact on yield, speed of ripening and the presence of vitamins in the grown tomatoes (e.g. the lycopene concentrations; Potopová *et al.*, 2017*b*).

Modelling the interactions between several competing events is more complex than modelling the drivers of individual events (Potopová *et al.*, 2021). Dynamic crop simulation models can be a useful tool to simulate the wide-ranging effects of CEs on vegetable production where impacts depend on multiple dependent weather-soil variables and crop management. The crop models calculate expected growth and development based on equations that describe how a crop, as a community of plants, responds to soil and weather conditions (Hoogenboom *et al.*, 2019). Computer simulation models of the soil-plant-atmosphere system can make a valuable contribution to both improving crop performance and predicting environmental impacts in different management scenarios. Although crop models have a great potential for practical use, particularly in horticultural field production, their use remains limited (Gary *et al.*, 1998; Boote, 2017). Tomato has been a pioneer vegetable species for crop modelling. In recent decades, most of the tomato modelling effort has been put on carbon fluxes and development processes related to the crop environment (Boote *et al.*, 2012).

There are several crop growth models for tomato, some of which are adapted for greenhouse production and others for field production systems. Some examples are TOMGRO (Jones *et al.*, 1991), HORTISIM (Gijzen *et al.*, 1997), TOMSIM (Heuvelink and Bertin, 1994), TOMPOUSSE (Gary *et al.*, 1996) and SIMULTOM (Sauviller *et al.*, 2002). In field production, modelling has been focused on predicting harvest date and dry matter production, as well as to estimate water and nutrient requirements. The CROPGRO-Tomato model was adopted by Scholberg *et al.* (1997) to simulate field-grown tomato. Boote *et al.* (2012) developed a module for predicting fresh tomato weight and fruit size, which was added to the

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Potential of Community Volunteers in Flood Early Warning Dissemination: A Case Study of Bangladesh

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Abstract: Flood early warning (FEW) is a vital component of disaster risk management and is particularly important for saving lives, developing a sustainable agro-based economy, economic stability, and the overall development of the people of Bangladesh as well as others. This study was conducted in a northern, flood-prone area of Bangladesh to investigate the potential of incorporating volunteers of the community to the Union Councils (UCs) to disseminate FEW alongside the top-down approach. Several studies have found that despite having a sophisticated flood forecasting technology, local communities are not reaping the benefits of it, as the existing dissemination system is inaccessible to most local people. Since risk communication takes place in a social context, this study investigated and thereby proposed that volunteerism, as a form of social capital or communal virtue, can potentially assist the community-based disaster management (CBDM) institutions in enhancing their capacity to reach the maximum population at times of flood risk. Therefore, it was confirmed that the trained volunteers need to be integrated into and endorsed by the national policy. In addition, this study also provides a number of recommendations connecting literature with policy documents of Bangladesh.

Keywords: flood early warning; flood response; community volunteerism; disaster volunteer group; resilience; governance and planning; disaster management; sustainability

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1. Introduction

Flooding is a major natural disaster in Bangladesh, considering the number of people affected as well as the frequency of occurrence. Dissemination of flood risk information is an important part of a flood forecasting and early warning system (FFEWS) [1]. The government of Bangladesh strengthened the Community-Based Disaster Management (CBDM) approach based on the Union Councils (UCs), the lowest tier of local government institutions in the country. Under each UC there is a Union Disaster Management Committee (UDMC) responsible for managing disasters at the community level. However, it was realized that further improvement in the process of disseminating flood information was needed to reach those at immediate flood risk [2].The primary goal of a Flood Early Warning (FEW)system is to increase the safety of the people and reduce the harmful impact of floods [3,4]. People need to know the risk factors, and they should understand the warning to cope with the coming flood [5]. Therefore, a FEW minimizes risk to life, helps

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Projection of 21st century irrigation water requirements for sensitive agricultural crop commodities across the Czech Republic

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ABSTRACT

This study quantified the crop water consumption, crop-specific irrigation requirements, and availability of water resources to catchments under climate change in the Czech Republic (CZ). Within the SoilClim model and BILAN-WATERES hydrological water balance modeling process, we tried to answer the question of whether there are at least theoretical water resources in the individual catchments of the CZ that could cover possible higher demands for irrigation. An ensemble of five global climate models under the moderate representative concentration pathway (RCP4.5) from the EURO-CORDEX initiative was chosen to project the future water use indicators. The irrigation water requirement indicators for the growing season (GS) of vineyards, hop gardens, orchards, vegetables, and fodder crops were calculated in 1143 catchments for two periods, 2031–2050 (Sc1) and 2061–2080 (Sc2), compared to the observed period 1961–2020 (Obs). To project irrigation scenarios in agricultural water management, the following water use indicators were quantified: relative soil moisture at 0–40 cm (*AWR1*) and 0–100 cm (*AWR*), crop water balance (*Rain-ET$_a$*), irrigation water requirement (*Irrig*), and the ratio of actual and reference evapotranspiration (ET_{ratio}). To assess areas with a critically low water supply and quantify the frequency of water deficit during the GS of each crop, we calculated the number of days with extreme values of water use indicators. Quantification of the extreme irrigation characteristics reflected the highest depletion of soil moisture and the highest water demands, i.e., when the assessed indicators reached the 25th percentiles. For highly marketable vegetables, the largest deficit in *Rain-ET$_a$* during the GS for Sc1 was projected. If current vegetable growing areas and cropping systems remain unchanged, *Irrig* will increase by 10.2% by the end of the 21st century under RCP4.5. Although current potato planting areas have soils with a high available water capacity, they will become controlled by the water deficit over the next few decades. The accumulated vineyard water required suggests that 15% and 25% of irrigation water will be lost by evaporation from the soil surface during the 2030s and 2080s, respectively. However, changes in future hopyard irrigation extent and amounts may have important implications in largely cropped irrigation hotspots. In the main traditional hop region for the 2030s, we project a 25% depletion of soil moisture and an increase of $ET_{ratio} < 0.4$ by up to 5.3%. The projection of a high frequency of days with an $ET_{ratio} < 0.4$ and $AWR1 < 30\%$ for fodder crops was related to the most risk-prone areas with an extreme lack of moisture in the regions with the most developed animal production. Thus, there will be insufficient fodder supply to the livestock sector due to any water stress during the production season under climate change conditions.

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Article

Water Consumption by Livestock Systems from 2002–2020 and Predictions for 2030–2050 under Climate Changes in the Czech Republic

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Abstract: The livestock system in Europe relies on a complex holistic equilibrium that is the outcome of an interplay of demand, market, crop production, livestock production, land use, water availability, and other factors. When modeling future scenarios of water consumption by livestock systems, the most suitable tools result from the interconnectivity of growth models, economic models, and climate models. We integrated the Environmental Policy Integrated Climate growth model (EPIC), animal-level model (RUMINANT), economic model (Global Biosphere Management Model, GLOBIOM), EURO-CORDEX climate models, and regression models. This study developed novel livestock production scenarios for individual regions of the Czech Republic with estimations of the categories of livestock that have been bred during the last 20 years and will be bred in the future and what their water consumption will be, both throughout the year and in particular seasons. First, the numbers of farm animals, namely, cattle, pigs, sheep, horses, goats, and poultry in 2002–2020 were evaluated, and their numbers were predicted for the following years until 2050. Second, livestock water consumption per region was determined based on the number of livestock individuals. Third, changes in the amount of water consumed by livestock per year in individual regions in 2050 compared to 2005 were estimated.

Keywords: thermal humidity index; cattle; pigs; sheep; horses; goats; poultry; global biosphere management model; food security

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1. Introduction

Livestock (cattle, pigs, sheep, horses, goats, and poultry, namely, hens, ducks, turkeys, and geese) is a source of 33% of the protein in human diets [1] as well as an important source of commodities consumed by people and provides many other services, such as traction, manure, risk management, and regular income [2]. Multiple extreme climate events (CEs) comprise a compound event and often result from a combination of climatic factors [3]. The direct and indirect effects of global warming, combined with the increasing frequency of weather extremes, are severe issues for livestock production, even in temperate climates such as central Europe [4–7]. The dual concept of feed losses and compound CEs has been suggested as an approach to understanding the extreme impacts of and reducing farmers' exposure to weather-related financial risks [8]. Sustainable fodder production for increasing livestock trends is exposed to an ensemble of CEs whose impacts are complex and difficult to assess [9]. CEs can contribute to increased vulnerability of water resources, which will affect the optimum water demand for fodder production to support the livestock sector. In that case, vulnerability assessment of optimum water resources for livestock, estimation of

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Calcium signalling in weeds under herbicide stress: An outlook

Katerina Hamouzová[1], Madhab Kumar Sen[1,2*], Rohit Bharati[3], Pavlína Košnarová[1], Md Rafique Ahasan Chawdhery[1], Amit Roy[2†] and Josef Soukup[1†]

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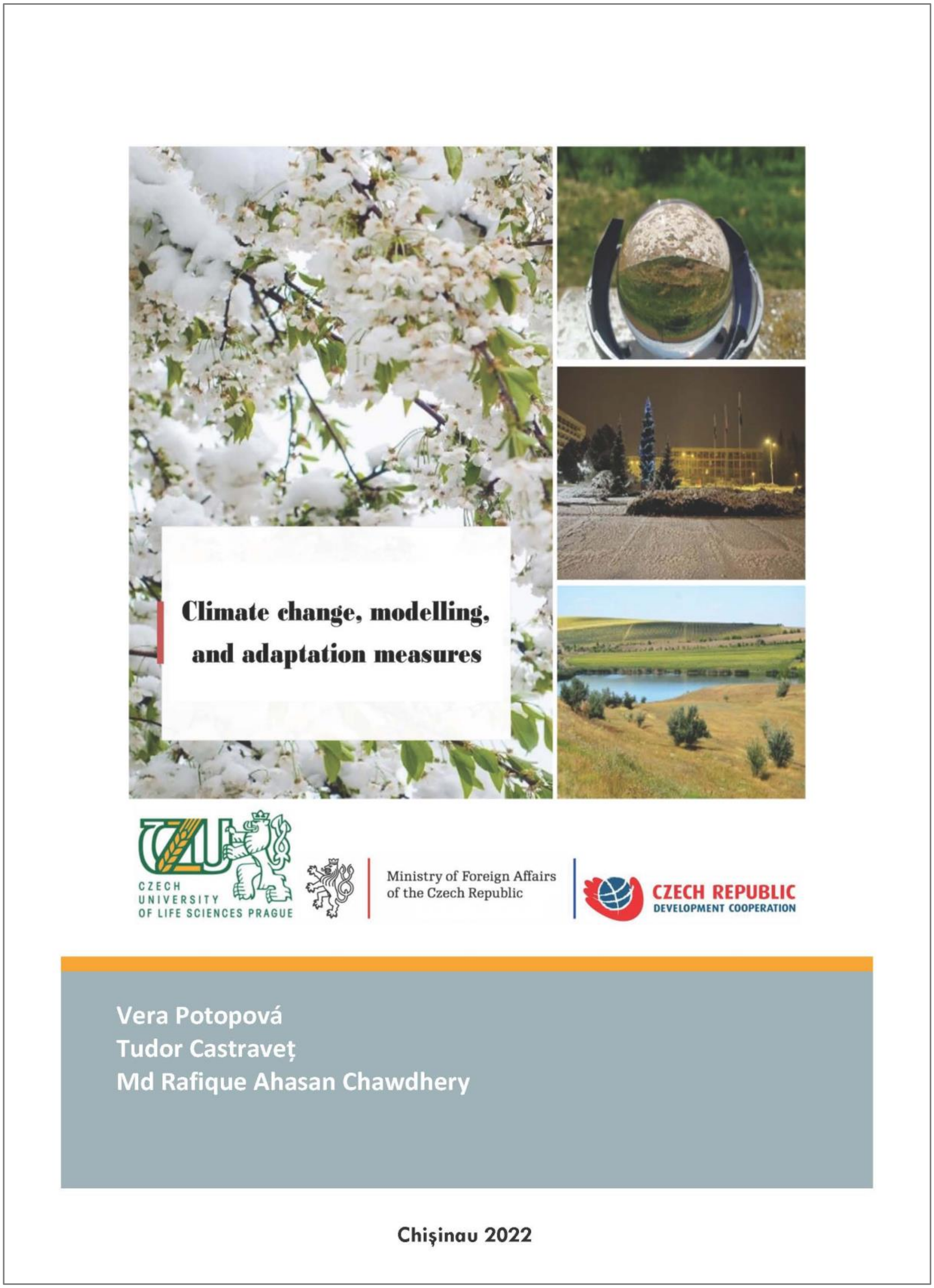
The continuous use of herbicides for controlling weeds has led to the evolution of resistance to all major herbicidal modes of action globally. Every year, new cases of herbicide resistance are reported. Resistance is still in progress in many species, which must be stopped before it becomes a worldwide concern. Several herbicides are known to cause stressful conditions that resemble plant abiotic stresses. Variation in intracellular calcium (Ca^{2+}) concentration is a primary event in a wide range of biological processes in plants, including adaptation to various biotic and abiotic stresses. Ca^{2+} acts as a secondary messenger, connecting various environmental stimuli to different biological processes, especially during stress rejoindering in plants. Even though many studies involving Ca^{2+} signalling in plants have been published, there have been no studies on the roles of Ca^{2+} signalling in herbicide stress response. Hence, this mini-review will highlight the possible sensing and molecular communication *via* Ca^{2+} signals in weeds under herbicide stress. It will also discuss some critical points regarding integrating the sensing mechanisms of multiple stress conditions and subsequent molecular communication. These signalling responses must be addressed in the future, enabling researchers to discover new herbicidal targets.

KEYWORDS
abiotic stress, calcium signalling, food security, herbicide resistance, weeds

1 Introduction

Plants cells are the depot for different ions, including calcium. Calcium (Ca^{+2}) is an essential bivalent cation with varying plant utilities (Aldon et al., 2018; Yadav et al., 2022). Calcium ions (Ca^{2+}) partake in several physiological parameters in plants, including cell division, cytoplasmic streaming, thigmotropism, photomorphogenesis, cell polarization, fruit development and ripening and plant microbe interaction (Gao et al., 2019; Furuichi, 2020; Eichstädt et al., 2021; Duo et al., 2022). Since the discovery of its effects on muscle

Books and practical methodology



Methodology for simulating crop production, water and nutrient management, climate risks and environmental sustainability in DSSAT

Czech University of Life Sciences Prague

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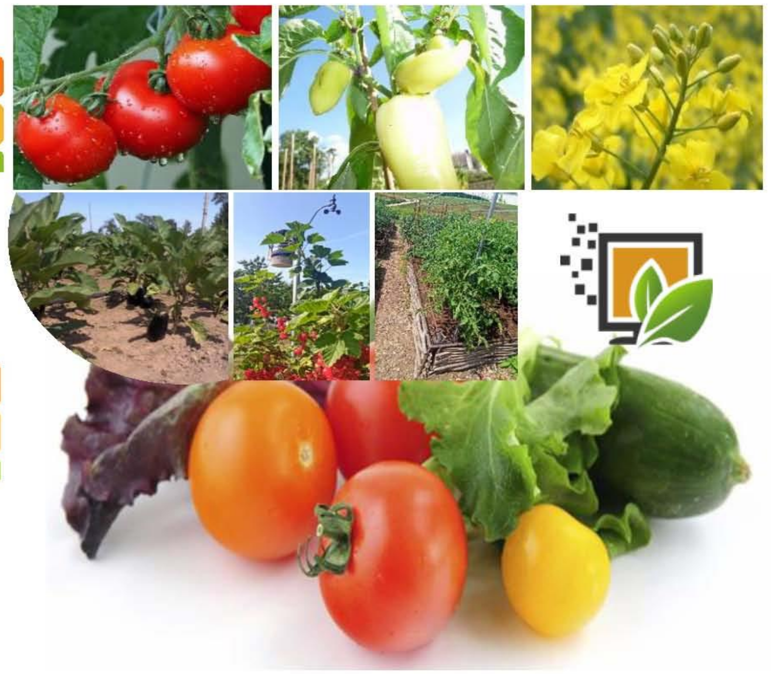

Modelling the impacts of compound climatic events on growth, development and yield parameters of field-grown thermophilic vegetables and oilseed rape in the Decision Support System for the Agrotechnology Transfer – DSSAT

Main Author

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1

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Modelování dopadů sdružených klimatických událostí na růst, vývoj a výnosové parametry polních teplomilných zelenin a řepky olejné v systému pro podporu rozhodování v oblasti transferu agrotechnologií – DSSAT

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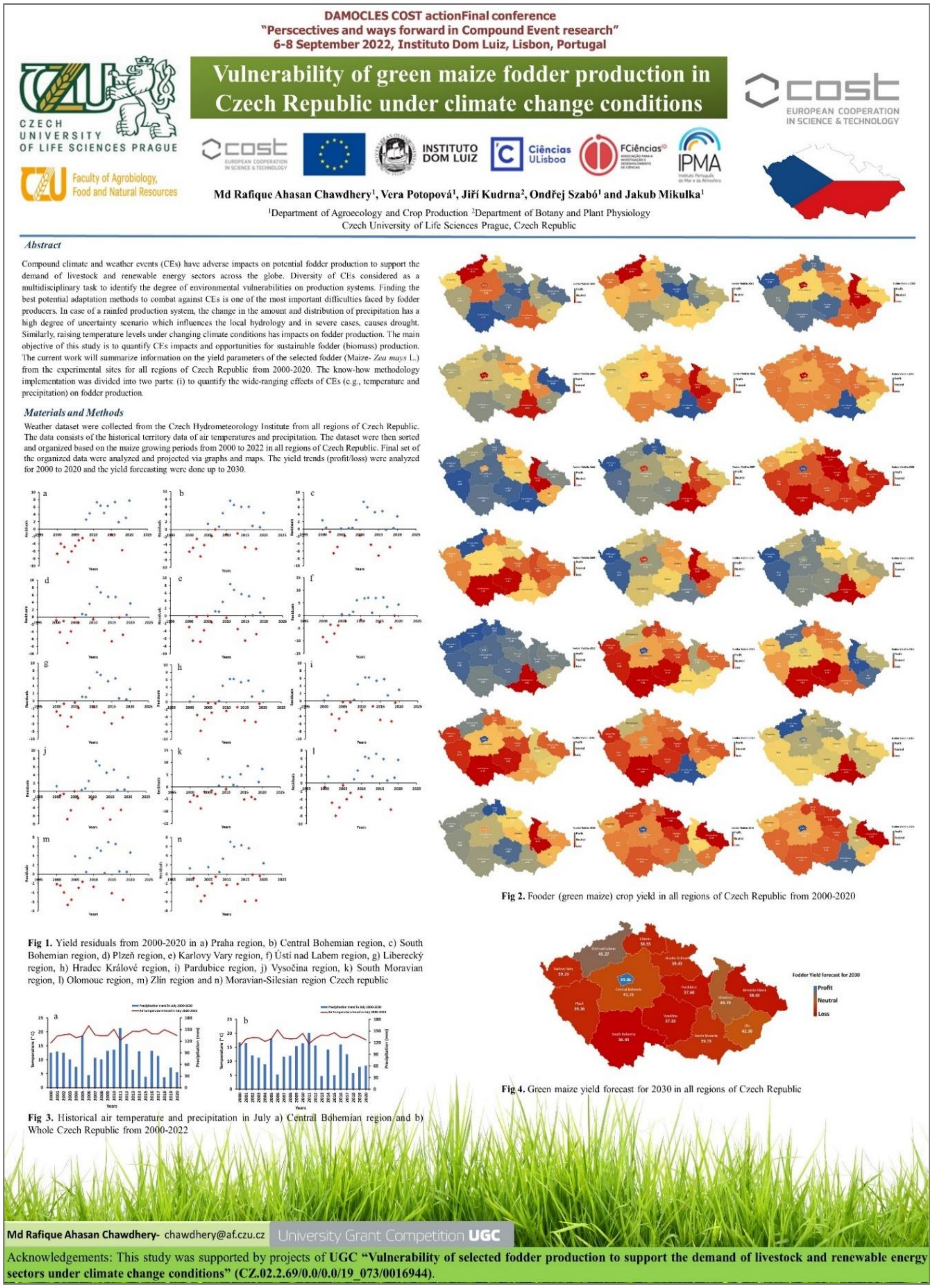

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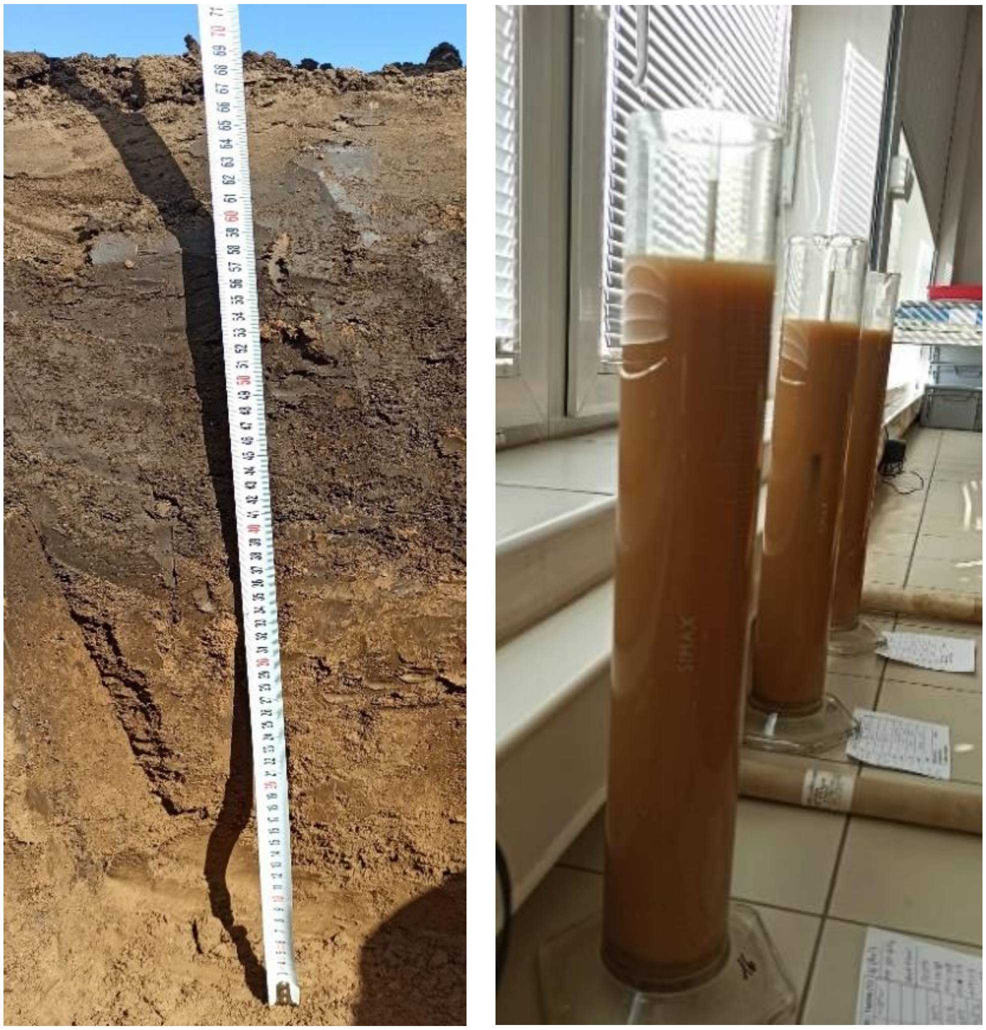
Appendices

Crop data collection activities



Soil sampling and laboratory analysis