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Modelling the impacts of climate change on the growth and development of thermophilic vegetables

Dissertation thesis

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Declaration

I hereby declare that I have authored the thesis carrying the name **“Modelling the impacts of climate change on the growth and development of thermophilic vegetables”** independently under the guidance of my supervisor. Furthermore, I confirm that I have used only professional literature and other information sources that have been indicated in the thesis and listed in the bibliography at the end of the thesis. As the author of the thesis, I further state that I have not infringed the copyrights of third parties in connection with its creation.

In Prague on date of submission ____________________________

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Abstract

The presented work is based on the relationship of crop growth models, and regional climate models with experimental fields as tools for predicting the development of the production process of thermophilic vegetables tested in the context of climate change. For research on thermophilic vegetables, soil-plant-atmosphere growth models included in the Decision Support System for Agrotechnology Transfer (DSSAT) models were used, and their results were validated by experiments under field conditions. For the first time, the ability of the CROPGRO-Tomato and CROPGRO-Pepper models to simulate growth, development, and yield parameters of thermophilic vegetables (pepper hybrid Superamy F1, Tornado F1 and Thomas F1 tomato varieties) in various pedoclimatic conditions in Elbe lowland region was investigated. This work provides a crucial information for the development of different possible adaptation scenarios for the model crops and for evaluating the effectiveness of adaptation measures. Scenarios were developed regarding the impact of climate risks on the soil-plant-atmosphere culture system in the context of climate change. In the environment module of DSSAT, temperature impact scenarios combined with an increase in CO_2 concentration or a decrease/increase in precipitation during tomato and pepper crop cycles have been developed. The median of simulated yields at the current CO_2 concentration, but an increase in air temperature by 1 °C and a 25% increase in total precipitation showed a yield of 21% compared to the median of experimental data. When comparing the simulation results with the increase of CO_2 at the Sc2 scenario level with the data from the field experiment, the model overestimated the result compared to the field experiment. This means that a simultaneous increase in air temperature by 2 °C and an increase of 670 ppm CO_2 compared to current conditions and with the current variability of precipitation, the model estimates a higher productivity of tomatoes and peppers. This positive effect exceeds the negative effect of increased air temperature and rainfall variability (when applying irrigation). Based on the evaluation by the combined climate and crop model, the favourable temperature for fruit ripening of tomato areas will increase in the Czech Republic corresponding with the probability of the occurrence of GDD >1000 °C. For the observed period (2001-2020), the area with the sum of effective temperatures for growing tomatoes (GDD >1000 °C) represents about 36.60 % of the territory. In the future, according to the climate models used, for the periods 2021-2040 and 2041-2060, the area with a probability of effective temperatures above 1000 °C will increase considerably.

Keywords:

Thermophilic vegetables, climate change, crop simulation model, DSSAT, spring frost, heat waves, LAI, dry biomass.

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List of symbols and abbreviations

T_{avg} – Average temperature

T_{max} – Maximum temperature

T_{min} – Minimum temperature

MJ m^{-2} d^{-1} – Global solar radiation in megajoule

P – Precipitation

RA – Atmospheric radiation

mm – Millimetres

°C – Degree Celsius

l – Litter

g – Grams

cm – Centimetres

kg/ha – Kilograms per hectare

t ha^{-1} – Tons per hectare

m – Meter

km^2 – Square kilometres

DSSAT – Decision Support System for Agrotechnology Transfer

CO_2 – Carbon dioxide

FAO – Food and Agriculture Organization of the United Nations

EPIC – Environmental Policy Integrated Climate

APEX – Agricultural Policy Environmental Extender Model

VegSyst – Vegetable Production Systems Simulation Model

SALTMED – Salinity and Temperature in the Mediterranean Sea

EU - Rotate – European Union Rotate crop model

TOMGRO – Tomato Growth Model

TOMSIM – Simulation model for tomato crop growth

INTKAM – Transpiration model

CSM – Cropping systems model

LAI – Leaf Area Index

LAI_{max} – Maximum Leaf Area Index

AGB – above-ground biomass

ČZU – Česká zemědělská univerzita v Praze

MO – Mochov

SU – Suchdol

LSL – Long shelf-life

ToMV – Tomato mosaic virus

TYLCV – Tomato yellow leaf curl virus

m a.s.l – Metres above sea level

BBCH scale – **B**iologische Bundesanstalt, **B**undessortenamt und **CH**emische Industrie

Mpx – Megapixels

UV filter – Ultraviolet filter

% – Percent

h – hour

m^2/ha – Square meter per hectare

m^2 m^{-2} – Square meter per square meter

RCMs – Regional climate models

CORDEX – European Coordinated Regional Climate Downscaling Experiment
WRCP - World Climate Research Program
RCP - Representative Concentration Pathway
SLCL - Clay content
SLSI - Dust content
SLSA - Sand content
BD - Bulk density
$cm^3\ cm^{-3}$ - Cubic centimetre per cubic centimetre
LL - Lower limit
DUL – Upper limit field capacity
C:N - Carbon and nitrogen
pH - Potential hydrogen
SLHV - pH of the soil solution
CEC - Cation exchange
SLOC - Total organic carbon content
SLNI - Total nitrogen content
SAT - Saturated water content
SRGF - Root growth factor
SLPF - Soil fertility factor
XBuild - Crop Management Module
DAP – Days after planting
GLUE - Generalized Likelihood Uncertainty Estimation
GDD - Growth degree days
T_b – Basic temperature
T_{opt} – Optimal temperature
Tl_{min} - lethal minimum temperature
Tl_{max} - Lethal lethal maximum temperature
Se - Standard error of estimate
MAE - Mean absolute error
RMSE - Root mean square error
ppm - Parts per million
Sc - Scenario
R^2 - Percentage of variance
SSP - Shared Socio-Economic Pathway
S - Simulated
M-Measure

1. INTRODUCTION

Population growth, which has a direct correlation with the amount of consumed food, makes relevant the research work focused on increasing agricultural production. One of such significant agricultural products are tomato, pepper, and eggplant, which became an indispensable part of the human ration, the yearly demand for which is only growing (Prohens-Tomás & Nuez 2008b, 2008a). Climate change has significant impacts on agriculture worldwide (Uprety et al. 2019). As global temperatures rise and weather patterns become more unpredictable, agricultural systems face numerous challenges that affect crop yields, water availability, and livestock health (Nelson et al. 2009; Wheeler & Von Braun 2013; Wang et al. 2017). Addressing the impact of climate change on agriculture requires comprehensive strategies, including sustainable agricultural practices, efficient water management, crop diversification, and the development and adoption of climate-resilient varieties (Ventrella et al. 2012; Parajuli et al. 2019; Valcárcel et al. 2020). Policy interventions and international cooperation are also essential to address the global nature of climate change and its implications for agriculture and food security (Georgopoulou et al. 2017; Uprety et al. 2019; Nendel 2023).

One way to evaluate the effects of climate change on the growth and development of thermophilic vegetables is to apply growth models (Nendel 2023). Crop modelling plays a crucial role in advancing our understanding of crop growth and productivity, supporting sustainable agricultural practices, and ensuring food security in a changing world. The growth model simulates a number of scenarios that can illustrate how the food system will respond to combined events of climate extremes. As a thermophilic crop, tomatoes are sensitive to thermal deviations, and rising temperatures at the global level caused by climate change are affecting cultivation (Boote et al. 2012a; De Lorenzi et al. 2017). Higher temperature values are already affecting tomato production in tomato-producing countries. The hot climate requires more irrigation during cultivation, which subsequently leads not only to an increase in water consumption but also affects the cost of production (Garofalo & Rinaldi 2015). In addition, hot weather has a negative impact on the quality of vegetables (Easterling et al. 2000; Moretti et al. 2010).

At the same time, climate change can also have a positive impact. Thanks to the temperature rise it became possible to extend the cultivation areas of thermophilic crops in other countries, where it was previously difficult or impossible to grow these crops, in the conditions of the open field. The cultivation of field crops in the Czech Republic is currently increasingly exposed to the effects of ongoing climate change (Potopová et al. 2017). Tomato (*Solanum Lycopersicum* L.), eggplant (*Solanum melongena* L.), and pepper (*Capsicum annum* L.) are thermophilic vegetables and a limiting factor for their profitable cultivation in the Czech Republic are the temperature conditions of the habitat. Open-field cultivation of tomatoes in the climate conditions of the Czech Republic remains only an auxiliary activity of vegetable producers (Potop et al. 2012). The agrometeorological conditions in the Czech Republic have been suitable for the cultivation of fruit and vegetables in the last decade, and the quality of the harvest is increasing, that in addition to the undoubted efforts of producers, is also a consequence of the ongoing climate change. The surface of areas with temperature conditions that satisfy the demands of thermophilic vegetables will increase in the Czech Republic (Potop et al. 2012; Potopová et al. 2017). For receiving precise data and a better understanding of the temperature influence on the development of crops, it is preferable to use a simulation model. For this purpose, it is necessary to perform additional careful studies focused on the research related to the simulation adaptability of thermophilic crops to climate change in order to determine the most suitable conditions and cultivation areas in the Czech Republic.

2. LITERATURE REVIEW

2.1 The nutritional composition and potential health benefits of thermophilic vegetables

Thermophilic vegetables offer various nutritional benefits and contribute to a well-rounded and healthy diet (Preedy & Watson 2019). The specific nutritional composition can vary among different vegetables, here are some general aspects and potential health benefits associated with thermophilic vegetables (Atherton & Jehoshua 1986; Benton Jones 2007; Hyman 2019; Preedy & Watson 2019):

1. *Vitamins and Minerals*: Thermophilic vegetables are often rich in essential vitamins such as vitamin A, vitamin C, and various B vitamins. These vitamins play crucial roles in maintaining healthy skin, boosting the immune system, and supporting overall growth and development. They also provide important minerals like potassium, magnesium, and folate, which are essential for maintaining proper cellular function, supporting bone health, and participating in various metabolic processes.
2. *Fiber Content*: Many thermophilic vegetables are excellent sources of dietary fibres. Fiber aids in digestion promotes regular bowel movements, and can contribute to a feeling of fullness, which may help with weight management. Adequate fibres intake is associated with a reduced risk of cardiovascular diseases, type 2 diabetes, and certain types of cancer.
3. *Antioxidants and Phytochemicals*: Thermophilic vegetables are known to contain a wide range of antioxidants and phytochemicals, including carotenoids (e.g., lycopene, beta-carotene), flavonoids, and phenolic compounds. Antioxidants help neutralize harmful free radicals in the body, reducing oxidative stress and protecting cells from damage. Some thermophilic vegetables, such as tomatoes and peppers, are particularly rich in antioxidants like lycopene, which has been associated with potential health benefits, including reducing the risk of certain cancers and promoting cardiovascular health.
4. *Hydration*: Many thermophilic vegetables, such as cucumbers and tomatoes, contain high water content, contributing to hydration when consumed. Proper hydration is essential for various bodily functions, including temperature regulation, digestion, nutrient absorption, and overall well-being.

5. *Low Calorie and Fat Content*: Thermophilic vegetables are generally low in calories and fat, making them suitable for weight management and maintaining a healthy diet. They provide essential nutrients and contribute to satiety without adding excessive calories or unhealthy fats.

6. *Potential Health Benefits*: Regular consumption of thermophilic vegetables, as a part of a balanced diet, has been associated with numerous health benefits, including reduced risk of chronic diseases such as heart disease, certain cancers, and obesity. The high content of vitamins, minerals, and antioxidants in thermophilic vegetables can support immune function, reduce inflammation, and promote overall well-being.

2.2 Studied crops

The crops investigated in this study belong to the Solanaceae family and include economically significant vegetables, namely tomato (*Solanum lycopersicum* L.), pepper (*Capsicum annuum* L.), and eggplant (*Solanum melongena* L.). These vegetables serve as valuable sources of dietary fibre, vitamins, minerals, and various beneficial phytochemicals (Benton Jones 2007; Hyman 2019).

2.2.1 Tomato

The tomato is native to the western coast of South America, specifically in the region of present-day Ecuador, Peru, and northern Chile. The domestication of tomatoes began over 2,000 years ago by indigenous peoples in the Andean region (Atherton & Jehoshua 1986; Hyman 2019). They selectively cultivated and bred wild tomatoes to produce larger, more desirable fruits. Early domesticated tomatoes were smaller and yellow in color. Over time, through natural and artificial selection, the red and larger-fruited varieties that we recognize today were developed (Hyman 2019). Tomatoes were first introduced to Europe by Spanish explorers in the 16th century. Initially, they were considered ornamental plants, grown for their attractive fruit, but not widely consumed (Atherton & Jehoshua 1986). Eventually, their culinary uses spread, and tomatoes became an essential ingredient in Mediterranean cuisine, particularly in Italy, where they are now a fundamental component of various dishes such as pasta, pizza, and sauces (Hyman 2019).

Tomatoes can be classified based on several criteria (Prohens-Tomás & Nuez 2008b, 2008a; Welbaum 2015). Here are some common classifications of tomatoes:

1. **Based on Growth Habit:**

a. Determinate Tomatoes: These tomatoes have a compact growth habit, reaching a predetermined height and setting fruit at once, making them suitable for smaller spaces and container gardening.

b. Indeterminate Tomatoes: These tomatoes continue to grow and produce fruit throughout the growing season and require more space and support due to their vining nature.

2. **Based on Shape and Size:**

a. Round Tomatoes: These are the most common tomatoes with a spherical shape and varying sizes, such as cherry tomatoes, salad tomatoes, and beefsteak tomatoes.

b. Plum or Roma Tomatoes: These tomatoes are oval or cylindrical in shape and have a meatier texture, making them ideal for sauces and canning.

c. Pear or Teardrop Tomatoes: These tomatoes have a shape similar to a pear or teardrop and are often used in salads and garnishes.

d. Grape or Cherry Tomatoes: Small and elongated, these tomatoes are typically sweet and used in salads or as snacks.

3. **Based on Colour**:

a. Red Tomatoes: These are the most common type, ranging from bright red to deep crimson when ripe.

b. Yellow Tomatoes: These tomatoes have a yellow or golden colour when ripe and are often milder and less acidic than red tomatoes.

c. Orange Tomatoes: These tomatoes have a vibrant orange colour when ripe and offer a sweet and tangy flavour.

4. **Based on Use**:

a. Fresh-eating or Salad Tomatoes: These are typically larger, juicy tomatoes with a balance of sweetness and acidity, perfect for eating fresh in salads or sandwiches.

b. Processing or Canning Tomatoes: These tomatoes are usually firmer and have less water content, making them suitable for making sauces, ketchup, and canned products.

c. Cherry and Grape Tomatoes: These small, sweet tomatoes are often used for snacking, in salads, or as garnishes.
d. Beefsteak Tomatoes: Large and meaty, these tomatoes are popular for slicing and using in sandwiches and burgers.

It's essential to note that there are numerous tomato cultivars and hybrids, resulting in a vast array of tomato types available for cultivation and consumption. The classification may vary depending on regional preferences and specific varieties developed by farmers and growers (Atherton & Jehoshua 1986; Benton Jones 2007).

Main countries producing tomatoes.

According to the official database of the Food and Agriculture Organization of the United Nations in 2021 (www.faostat.com), the main countries known for producing field tomatoes worldwide are as follows: China produces 67,636,724.84 tons of tomatoes, accounting for a substantial portion of the global tomato production. India is the second-largest producer of tomatoes. It cultivates 21,181,000 tons. The United States is one of the major tomato-producing countries, with a production volume of 10,475,265 tons. In Europe, the leading countries are Turkey with 13,095,258 tons, Italy with 6,644,790 tons, and Spain with 4,754,380 tons.

2.2.2 Pepper

Peppers are native to the Central and South America, specifically to regions that are a part of present-day Mexico, Guatemala, Belize, Honduras, Nicaragua, and northern South America. The domestication of peppers began around 6,000 to 10,000 years ago by indigenous peoples in these regions. Early domesticated peppers were likely small, spicy, and with various colours, ranging from red and yellow to orange and green (Cao et al. 2022).

During the age of exploration, European explorers brought peppers to Europe and other parts of the world during the Columbian Exchange in the 15th and 16th centuries. Peppers quickly spread across the globe, becoming an integral part of various cuisines and culinary traditions worldwide. Today, *Capsicum annuum* is one of the most widely cultivated and consumed pepper species globally, encompassing a diverse array of varieties and cultivars with varying shapes, sizes, colours, and levels of spiciness (Araceli et al. 2009; Cao et al. 2022).

Peppers belong to the Solanaceae family and are classified based on various criteria, including their botanical characteristics, spiciness levels, and intended culinary use. Here are the primary classifications of peppers:

1. **Species Classification:**

a. *Capsicum annuum*: This species includes a wide range of peppers, including bell peppers, sweet peppers, cayenne peppers, and many chili pepper varieties. They vary in shape, size, colour, and spiciness levels (Prohens-Tomás & Nuez 2008a, 2008b).

b. *Capsicum frutescens*: This species includes some of the spicier peppers, such as tabasco peppers and Thai bird's eye chili.

c. *Capsicum chinense*: This species includes some of the hottest peppers in the world, including the famous Carolina Reaper, Bhut Jolokia (Ghost Pepper), and Trinidad Scorpion.

2. **Spiciness Levels:**

a. Sweet Peppers: These peppers have little to no spiciness and are commonly used in cooking due to their mild and sweet flavour. Examples include bell peppers and banana peppers.

b. Mild Peppers: These peppers have a hint of spiciness but are generally considered mild. Examples include poblano peppers and Anaheim peppers.

c. Moderately Hot Peppers: Peppers in this category have a moderate level of spiciness. Examples include jalapeño peppers and serrano peppers.

d. Hot Peppers: These peppers are noticeably hot and can add a significant kick to dishes. Examples include cayenne peppers and Thai chili peppers.

e. Very Hot Peppers: The peppers in this category are extremely spicy and are usually used sparingly. Examples include habanero peppers and Scotch bonnet peppers.

f. Super-Hot Peppers: These peppers are among the hottest in the world, with extremely high levels of spiciness. Examples include Carolina Reaper, Trinidad Moruga Scorpion, and Naga Viper.

3. **Culinary Use:**

a. Fresh Eating Peppers: Peppers in this category are commonly consumed raw in salads or as a snack due to their mild and sweet flavour. Examples include bell peppers and sweet mini peppers (Araceli et al. 2009).

b. Cooking Peppers: These peppers are used in various cooked dishes, sauces, and stews due to their mild to moderately hot flavours. Examples include poblano peppers and jalapeño peppers.
c. Hot Sauce Peppers: Peppers with higher spiciness levels are often used to make hot sauces and spicy condiments. Examples include cayenne peppers and Thai chili peppers.

Main countries producing peppers.

In accordance with the data sourced from the official database of the Food and Agriculture Organization of the United Nations for the year 2021 (“www.faostat.com”), the primary countries distinguished for their global peppers production grown in the open field are as follows: China is the largest producer of peppers in the world. It produces 16,749,718.83 tons, including various types such as sweet peppers, chili peppers, and bell peppers. Mexico is one of the leading pepper-producing countries, with a production of 2,584,143.6 tons. Mexico is known for its diverse pepper varieties, including jalapeños, serranos, and poblano peppers. Indonesia is a significant producer of peppers, primarily chili peppers, with a production of 2,747,018.03 tons. In Europe, the countries that hold a leading position in terms of pepper production are as follows: Turkey is a major producer of peppers, particularly chili peppers. That produced 3,091,295 tons of peppers. Spain is a prominent pepper producer in Europe. It cultivates various types of peppers, including bell peppers and piquillo peppers, with a production of 1,511,560 tons. Italy is known for its production of peppers around 244,050 tons, including sweet peppers and chili peppers, used in traditional Italian dishes and cuisine.

2.2.2 Eggplant

Eggplants have a history that dates back thousands of years and spans across different regions of the world (Gürbüz et al. 2018). The exact origins of eggplants are not definitively known, but it is believed that they were first domesticated in South Asia, particularly in the region that includes India and Bangladesh. The domestication of eggplants likely began around 4,000 to 6,000 years ago in the Indian subcontinent. Early cultivators selectively bred the wild eggplants to develop larger, less bitter fruits with varying shapes, colours, and culinary uses (Meyer et al. 2012).

From India, the cultivation of eggplants spread to other parts of the world through trade and cultural exchanges. The ancient Greeks and Romans were introduced to eggplants around 2,000 years ago, where they were known as "melongena" in Greek, leading to the scientific name "*Solanum melongena*". Eggplants were later introduced to other parts of Europe, including Italy and the rest of the Mediterranean region. In the 15th century, the eggplant made its way to the Middle East and eventually reached the New World during the European colonization of the Americas (Prohens-Tomás & Nuez 2008b, 2008a; Welbaum 2015).

Today, eggplants are cultivated and consumed in various countries around the world and have become a staple ingredient in many cuisines. They are used in a wide range of dishes, from Mediterranean moussaka to Middle Eastern baba ganoush and Asian stir-fries.

Eggplants are classified based on several criteria, including their shape, colour, size, and intended culinary use. Here are some common classifications of eggplants:

1. Based on Shape and Size:

a. Standard or Globe Eggplants: These are the most common eggplants with a large, rounded, or oval shape and smooth, glossy skin. They come in various colours, including purple, black, white, and striped varieties.

b. Japanese or Oriental Eggplants: These eggplants are long and slender, with thinner skin compared to standard eggplants. They are typically purple, green, or white in colour.

c. Italian Eggplants: Also known as Graffiti or Sicilian eggplants, these have a bulbous base that tapers into a teardrop shape. They are often purple with white streaks.

2. Based on Colour:

a. Purple Eggplants: These are the most common type, ranging in shades of deep purple to nearly black when ripe.

b. White Eggplants: White eggplants have a creamy-white skin and a milder flavour compared to purple varieties.

c. Green Eggplants: Green eggplants have a pale green skin and are known for their slightly bitter taste.

3. Based on Culinary Use:

a. Standard Eating Eggplants: These are the most versatile eggplants and are commonly used in various dishes, such as stir-fries, curries, and roasted vegetables.

b. Italian Eggplants: These eggplants are often used in Mediterranean dishes, such as eggplant Parmesan and ratatouille.
c. Asian Eggplants: Japanese and other Asian eggplants are preferred in many Asian cuisines due to their tender texture and mild flavour.

These classifications are not exhaustive, as there are many cultivars and regional varieties of eggplants, each with unique flavours and culinary applications. The choice of eggplant type often depends on personal preference, cultural traditions, and specific recipe requirements.

Main countries producing eggplants.

The production of eggplants can vary from year to year due to factors such as weather conditions, market demand, and agricultural practices. Here are some of the main countries known for producing eggplants in the open field and their production amounts according to "FAOSTAT" 2021: China is the largest producer of eggplants globally (www.faostat.com.) It cultivates a wide variety of eggplant types and produced 37,459,233.66 tons of eggplants. India is also a major producer of eggplants and is one of the leading eggplant-producing countries (12,874,000 tons of eggplants). Egypt is a significant producer of eggplants in the Middle East and North Africa region, with an annual production of approximately 1,286,469.74 tons. In Europe, the leading countries are Turkey with 832,938 tons, Italy with 306,440 tons, and Spain with 265,290 tons.

2.3 Agriculture and climate change in Europe

The European climate is predominantly characterized as temperate. Western Europe is influenced by the Atlantic Ocean and the Gulf Stream, which results in warm summers, cool winters, and frequently overcast conditions with substantial rainfall along the coastal regions and extending up to approximately 500 km inland. In contrast, Southern Europe experiences a Mediterranean climate according to the Köppen classification (Köppen W. 1900), featuring hot and dry summers and relatively mild winters, with significantly less precipitation compared to the winters in Western Europe. Towards the eastern regions, a continental climate prevails, characterized by hot summers and cold winters, leading to significant annual temperature fluctuations. In recent decades, a notable shift in these climatic zones has been observed due to ongoing climate change (Anyamba et al. 2014). Across Europe, the majority of regions experience four distinct seasons, while in the Mediterranean Basin, a distinct wet and dry season pattern dominates, with the rainy season typically spanning from October to February. These seasonal patterns play a pivotal role in shaping agricultural practices and have contributed to the current landscape of agricultural land, regulations, and techniques that have evolved over time.

Climate change is anticipated to exert an impact on the spatial distribution of prevalent adverse weather events that significantly affect agriculture (Figure 1) (Trnka & Hlavinka 2020). Excessive rainfall is expected to persist as the primary constraint for crop and fodder production in extensive regions along the north-western coastal area of the continent and the British Isles. Meanwhile, snow will continue to restrict production in the northeastern and eastern regions as well as in Alpine areas. In contrast, drought is projected to emerge as the predominant limiting factor for crop and grass production across a substantial portion of the Mediterranean region (Sordo-Ward et al. 2019). Heat stress, on the other hand, is foreseen to predominantly affect smaller areas in Turkey and central Europe. Low temperatures currently constitute the predominant factor contributing to adverse weather events in certain regions of Scandinavia and central Europe. Simultaneously, issues related to snow and inconveniently low temperatures are expected to persist as major concerns in eastern and north-eastern Europe, as well as in the Alpine region. Remarkably, even under the relatively moderate RCP4.5 emission scenario, three global climate models (GCMs) concur on a significant rise in the likelihood of heat and drought stress (Trnka & Hlavinka 2020).

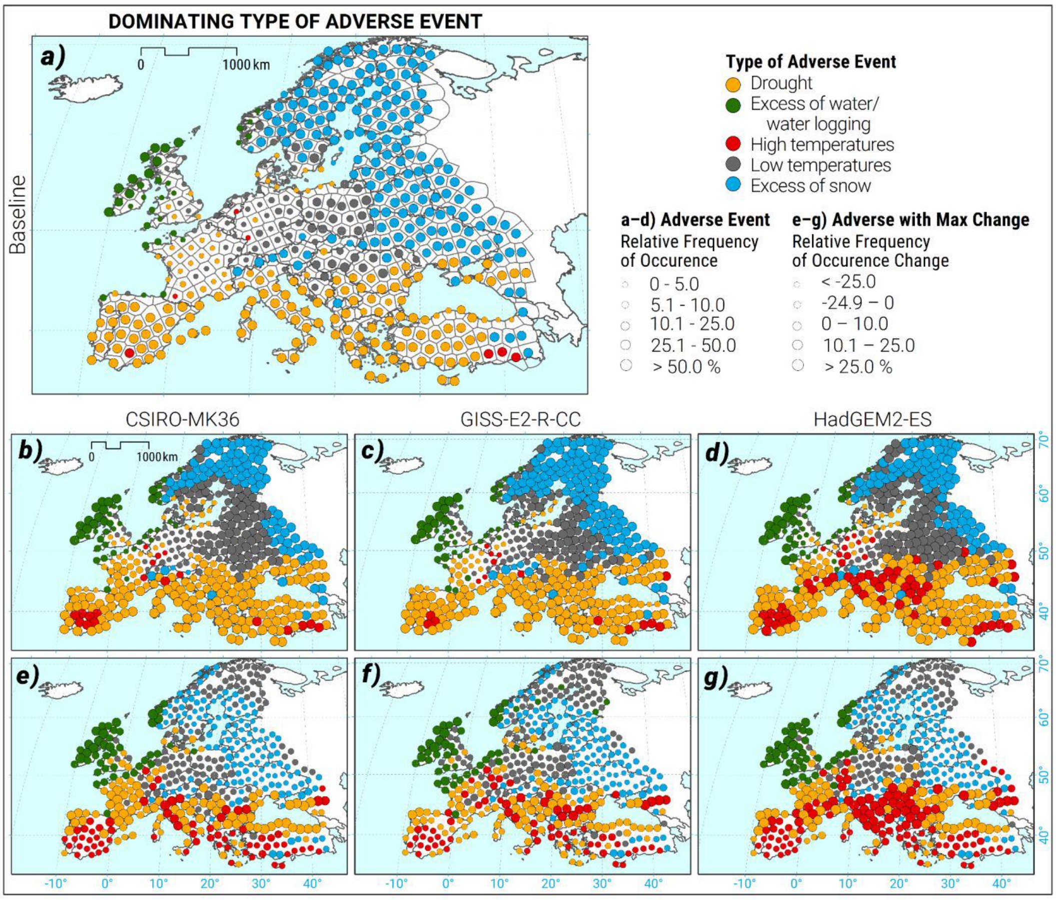

Figure 1. Types of adverse events for croplands and grasslands

((a) their expected frequency for (a) the baseline period (1981-2010) and (b-d) under future (2041-2060) climate conditions according to three GCMs, with the size of the circle corresponding to the event frequency. Panels (e-g) show the type of adverse event that exhibited the largest change compared to the baseline for the three considered GCMs: (b, e) CSIRO-RCP4.5), (c, f) GISS-RCP4.5, and (d, g) HadGEM-RCP4.5) Source: Trnka et al. (2020)

In recent years, agriculture and its primary production have experienced a resurgence in significance, despite being perceived as a sector of declining importance over the past centuries. This renewed attention can be attributed to several factors. Firstly, agriculture plays a crucial role in shaping the European landscape, and its impact extends beyond food production to encompass a wide range of essential ecosystem services, such as water provisioning, biodiversity conservation, recreational opportunities, and cultural values. The well-being and effectiveness of these ecosystem services are intimately connected with the conditions, financial resources, and motivations of farmers (Nendel 2023).

2.4 Impact of climate change on field vegetable production

The growth of the population has a direct interconnection with the quantity of food consumption, making actual the research work directed to the increase of agricultural production (Prohens-Tomás & Nuez 2008b, 2008a). Thermophilic vegetables are important agricultural products, which have become an indispensable part of the human diet, the annual demand for which is only increasing (Morris & Taylor 2017; Mason-D’Croz et al. 2019).

Climate change has significant impacts on field vegetable production, affecting various aspects of the agricultural system and posing challenges to farmers and food security (Wheeler & Von Braun 2013). Changes in temperature and precipitation patterns can lead to shifts in growing seasons for vegetables. Warmer temperatures may result in earlier planting and harvesting, while altered rainfall patterns can affect the timing of irrigation and planting, impacting crop yields and quality (Parry et al. 1988a; Bisbis et al. 2018). Extreme heat events can cause crop failures and reduce the productivity of heat-sensitive vegetables. Changes in precipitation patterns and increased evaporation can lead to water scarcity and drought conditions (Wheeler et al. 2000; Lobell et al. 2007). Reduced water availability affects vegetable crops' water uptake, leading to water stress and decreased productivity (Wakchaure et al. 2020; Lu et al. 2021). On the other hand, climate change may also lead to increased intensity and frequency of heavy rainfall events, causing waterlogging and flooding in fields. Excessive water can damage vegetable crops, disrupt nutrient absorption, and promote the spread of waterborne diseases. Climate change can alter the distribution and abundance of pests and diseases, impacting field vegetable production (Litskas et al. 2019a). Warmer temperatures may favour the proliferation of certain pests, leading to increased pest pressure and the need for more intensive pest management practices (Savary et al. 2019). Elevated levels of carbon dioxide in the atmosphere, a consequence of climate change, can affect the nutritional composition of vegetables (Dong et al. 2018; Kumari et al. 2019). Some studies suggest that increased CO_2 levels may reduce the protein, mineral, and vitamin content of certain crops, affecting their overall nutritional value (Dong et al. 2020a). The elevated content of the CO_2 in the atmosphere of anthropogenic provenience, which is considered as one of the main reasons of climate change, can positively influence the yield of vegetables (Dong et al. 2020b). According to the results of some research, the increase in CO_2 will contribute to improving leaf photosynthesis of crops, in case of suitable cultivation conditions - with favourable cultivation temperatures, without droughts (Leisner 2020; Tran et al. 2017).

Thanks to the temperature rise, the extension of the cultivation areas of thermophilic crops became possible. Especially in other countries, previously in which the growth of these crops was difficult or impossible, in the conditions of the open field. The development and extension of cultivation areas of thermophilic vegetables is possible but it requires additional research (Garofalo & Rinaldi 2015; Giuliani et al. 2019a).

Addressing the impact of climate change on field vegetable production requires adopting climate-smart agricultural practices and implementing sustainable adaptation strategies (Tran et al. 2017). These may include improved irrigation methods, the use of heat-tolerant crop varieties, water-efficient techniques, integrated pest management, and investment in a climate-resilient agricultural infrastructure. Additionally, fostering research and innovation in agriculture and enhancing the capacity of farmers to adapt to changing conditions are crucial for building a resilient and sustainable vegetable production system in the face of climate change.

2.5 Open field thermophilic vegetables in central Europe

In central Europe, where the climate can be cooler and experience distinct seasons, growing thermophilic vegetables in the open field can be more challenging compared to regions with consistently warmer temperatures (Parry et al. 1988b). However, with careful selection of suitable varieties and attentive cultivation practices, it is possible to grow certain thermophilic vegetables in the open field during the warmer months (Litskas et al. 2019a). Some thermophilic vegetables that can be cultivated in the open field in central Europe are tomatoes, peppers, cucumbers, melons, and eggplants.

It's important to know that successful open-field cultivation of thermophilic vegetables in central Europe depends on several factors, including regional climate, soil conditions, and the specific microclimate of the growing site. Using techniques such as selecting appropriate varieties, providing adequate soil preparation, mulching to retain heat and moisture, and optimizing planting times can all contribute to more successful results (Potopová et al. 2016, 2023a).

Growers in central Europe may also consider using season-extension methods like low tunnels or row covers to protect plants from late frosts and extend the growing season. Additionally, selecting varieties bred for cooler climates and shorter growing seasons can improve the chances of successful open-field cultivation.

Climate change has a range of impacts on field vegetable production in the Czech Republic, influencing agricultural practices, yields, and economic aspects of vegetable farming. Rising temperatures and changing precipitation patterns in the Czech Republic can lead to shifts in the growing seasons for vegetables. Warmer springs and longer growing seasons might allow earlier planting and extended harvest periods. However, unpredictable weather events, such as late frosts or early heatwaves, can also disrupt planting schedules and affect crop development. The increased frequency and intensity of heat waves can cause heat stress to vegetable crops, especially during the summer months. Heat stress can reduce plant growth, decrease flowering, and lead to reduced fruit development, resulting in lower yields and reduced crop quality (www. eagri.cz;Potopová et al. 2017).

2.6 Meteorological risk events for vegetable production in the Czech Republic

In terms of limiting the cultivation and introduction of non-traditional species, vegetables can be divided into three groups: thermophilic (origins typically in the tropics and subtropics), which stop growing at temperatures below 10 °C; cold-tolerant, which can tolerate cold below 0 °C for a short period of time; and frost-tolerant, which can resist mild frosts and can survive winters in some of our regions (Potop & Türkott 2014; Potop et al. 2014a, 2014b). Tomato, pepper, and eggplant are among the thermophilic vegetables, and the limiting factor for the profitable cultivation of these vegetables in the Czech Republic is the temperature conditions of the habitat. Field cultivation of tomatoes in the climatic conditions of the Czech Republic is, so far, only a secondary activity of vegetable farms (Potopová et al. 2017, 2020). In the Czech Republic, agro-meteorological conditions have been suitable for fruiting vegetables in the last decade, and the quality of yields has been increasing, which, in addition to the efforts of growers, is the result of the ongoing climate change (Potopová et al. 2022). However, some of the key meteorological risk events for vegetable production in the Czech Republic include:

1. Drought: Periods of prolonged drought can have severe consequences for vegetables. Insufficient rainfall and water shortages can lead to reduced crop yields and difficulties in irrigation (Potop et al. 2012).

2. Excessive rainfall and flooding: Heavy and persistent rainfall can cause flooding in fields, leading to waterlogged soils, crop damage, and loss of nutrients. Floods can also affect infrastructure, transportation, and damage farmland (Rezacova et al. 2005).

3. Hailstorms: Hailstorms during the growing season can cause extensive damage to crops, particularly fruits, vegetables, and other sensitive plants.

4. Frost: Late spring or early autumn frosts can damage or kill sensitive crops and plants, affecting yield and harvest.

5. Extreme Heat: Heatwaves during the growing season can stress crops and reduce yields. Rapid and extreme fluctuations in temperatures can be detrimental to plants, affecting growth (Potopová et al. 2023a, 2023b).

To mitigate the impact of meteorological risk events on agriculture, farmers in the Czech Republic often adopt various adaptation strategies. These may include the use of drought-resistant crop varieties, improved irrigation systems, soil conservation practices, early warning systems for extreme weather events, and insurance coverage to cope with losses caused by adverse weather conditions. The Czech Hydrometeorological Institute (www.chmi.cz) plays a crucial role in monitoring weather patterns and providing timely weather forecasts and warnings to support agricultural planning and decision-making. Other portals that provide information on the weather forecast for the selected crops are www.agropocasi.cz, www.agrorisk.cz).

The regional climate models are expected to impact evapotranspiration, a critical aspect of crop cultivation and the primary determinant of irrigation needs for lowland regions in the Czech Republic. The Czech Republic's agriculture is already facing challenges related to compound climate events and less-developed irrigation systems. As climate change progresses, these issues may become more pronounced and require comprehensive strategies to address their effects on crop productivity and water management in the region (Trnka et al. 2014; Balvín et al. 2021; Muntean et al. 2021). The irrigation water demand is contingent upon the specific water needs of each crop type and the availability of water from local sources (Garofalo & Rinaldi 2015). The quantity of water necessary for cultivation varies depending on the crop's characteristics and the hydrological conditions of the region. Assessing these factors is essential in determining the optimal irrigation practices to ensure sustainable and efficient water usage in agricultural systems (De Lorenzi et al. 2017).

Figures 2-4 show the water requirements to cover the moisture deficit and water need to ensure stable yields of vegetables for two periods, 2031–2050 and 2061–2080, compared to the observed period 1961–2020, and quantification of the availability of water resources to catchments and the contribution of the use of irrigation systems to mitigate the effects of drought (Potopová et al. 2022).

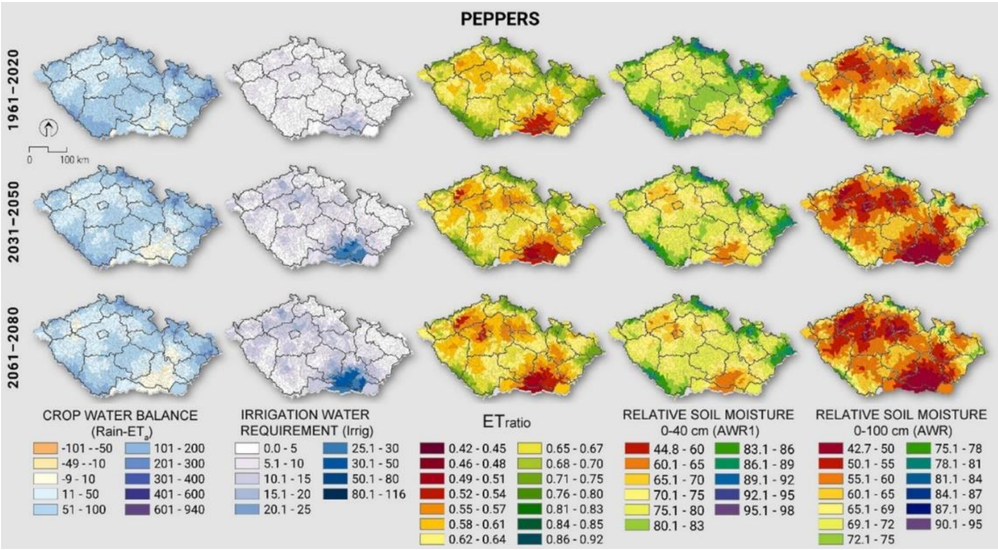

Figure 2. Crop water balance, irrigation water requirement

(The ratio of actual and reference evapotranspiration, relative soil moisture at 0-40 cm and 0-100 cm during growing season for peppers for the observed period (1961–2020) and two future periods under RCP 4.5 (2031–2050 and 2061–2080)). Source: Potopová et al. (2022)

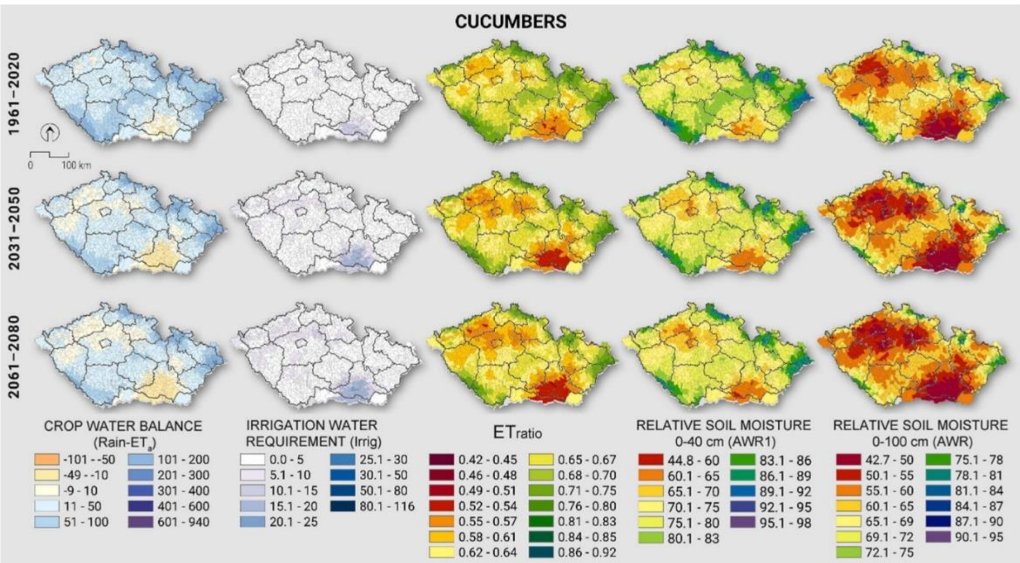

Figure 3. Crop water balance, irrigation water requirement
(The ratio of actual and reference evapotranspiration, relative soil moisture at 0-40 cm and 0-100 cm during growing season for cucumbers for the observed period (1961–2020) and two future periods under RCP 4.5 (2031–2050 and 2061–2080)). Source: Potopová et al. (2022)

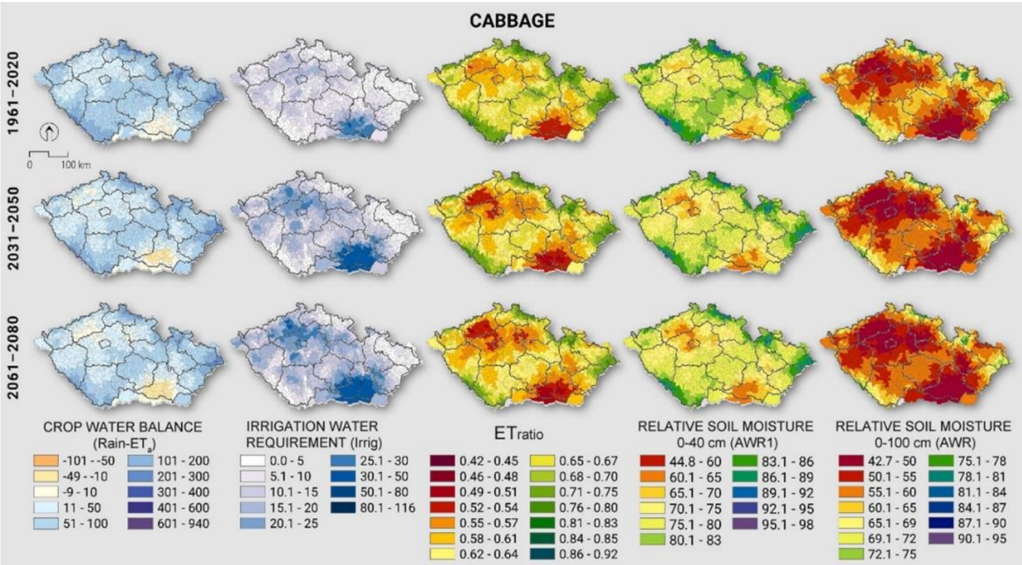

Figure 4. Crop water balance, irrigation water requirement
(The ratio of actual and reference evapotranspiration, relative soil moisture at 0-40 cm and 0-100 cm during growing season for cabbage for the observed period (1961–2020) and two future periods under RCP 4.5 (2031–2050 and 2061–2080)). Source: Potopová et al. (2022)

2.7 Models for simulating growth parameters of tomato and pepper under field and greenhouse conditions

Crop modelling, also known as crop simulation or agricultural modelling, is a scientific approach used to predict and understand the growth, development, and yield of crops under various environmental conditions. It involves the use of mathematical models and computer simulations to simulate the behaviour of crop plants and their response to different factors, such as weather, soil, management practices, and pest and disease pressures (Dayan et al. 1993; Heuvelink 1995a; Boote & Scholberg 2006).

Crop models are built based on scientific principles, empirical data, and knowledge of plant physiology, agronomy, and climatology. They integrate information about the crop's biology, growth stages, and interactions with the environment to make predictions about how the crop will perform under specific conditions (Rinaldi et al. 2007).

The main components of a crop model include:

1. Crop Growth Sub-model: This component describes the processes of plant growth and development, including germination, emergence, leaf area expansion, flowering, fruit set, and grain filling. It takes into account factors such as temperature, light, water availability, and nutrient availability.

2. Environmental Sub-model: This part of the model incorporates weather data (temperature, rainfall, solar radiation, etc.), soil characteristics (such as soil moisture, nutrient content, and texture), and other environmental factors that influence crop growth.

3. Management Sub-model: It includes information about agricultural practices such as planting date, irrigation, fertilization, pest and disease control.

4. Output Module: This component generates the output of the model, which may include predictions of crop yield, biomass, water use, nutrient uptake, and other relevant variables.

Crop models are valuable tools for agricultural decision-making, as they can help farmers, researchers, and policymakers optimize crop production, improve resource use efficiency, and mitigate the impacts of climate change (Aguiar et al. 2018). By running simulations under various scenarios, crop models can be used to assess the potential effects of climate variability, explore the suitability of specific crop varieties for different regions, and develop strategies to adapt agriculture to changing environmental conditions (Vermeulen et al. 2018).

Although crop models have great potential for practical applications, especially for vegetable field production, their use is still limited. Tomato is a pioneering vegetable for crop modelling (Table 1). A limited number of models are available for eggplant, e.g., APEX and EPIC (Williams & Izaurralde 1984).

Table 1. Models for simulating growth parameters of tomato and pepper under field and greenhouse conditions.

Nr	Model name	Model description	Reference
1	CROPGRO Tomato /Pepper	The modular structure of DSSAT contains an excellent model known as CROPGRO. The power of CROPGRO is to predict the phenology, growth, development, and nitrogen accumulation of sites representing different environmental and agronomic management scenarios. The CROPGRO Pepper model can be used to simulate the growth, development, and yield of planted pepper given inputs related to the soil-plant-atmosphere system.	(Scholberg et al. 1997; Rinaldi et al. 2007) .
2	SALTMED	It has been developed as a general model that can be applied to different irrigation systems, soil types, crops and trees, water application strategies (deficit irrigation, partial root drainage, subsurface irrigation), different nitrogen applications (fertigation, chemical or organic applications or application of plant residues to the soil), different water qualities and drainage systems.	(Rameshwaran et al. 2015; Silva et al. 2017).
3	EU – Rotate	It is a dynamic soil-plant-atmosphere deterministic model developed mainly for vegetable crop rotations. The model takes into account carbon and nitrogen mineralization and dynamics of soil organic matter, soil inorganic nitrogen, nitrogen losses to the environment, water balance, root growth, crop growth, nitrogen uptake, market yield, and economic return, which are influenced by environmental factors such as water, temperature, snow and frost, and agronomic practices including fertilization.	(Soto et al. 2014; Fazel et al. 2017).
4	TOMGRO	It describes the phenological development and dry matter accumulation of different plant organs from the date of planting to the last harvest under dynamically changing solar radiation intensity, greenhouse temperature, and CO_2 concentration.	(Jones et al. 1991; Giuliani et al. 2019b).
5	TOMSIM	It was developed for greenhouse tomatoes, and the following sub-modules were validated: (1) greenhouse permeability, (2) photosynthesis, (3) dry matter production, and (4) canopy aspect, fruit growth period, and dry matter distribution.	(Heuvelink 1995b, 1996; Heuvelink & Buiskool 1995).
6	EPIC	It is a cropping systems model that was developed to estimate the productivity of land affected by erosion as part of soil and water management. It simulates the growth and development of approximately 80 crops (e.g., tomato, pepper, and **eggplant**) using unique parameter values for each crop. It predicts the effects of management decisions on the movement of water, nutrients, and pesticides in the soil and their combined impact on soil loss, water quality, and crop yields.	(Williams & Izaurralde 1984; Cavero et al. 1998; Garofalo & Rinaldi 2015).
7	APEX	It simulates the growth and development of tomato, pepper, and **eggplant** at the farm level and integrates	(Gassman et al. 2004).

		surface water runoff and nutrient cycling.	
8	VegSyst	It was developed to calculate the daily nitrogen fertilizer requirement, irrigation, and nitrogen concentration in the applied nutrient solution for fertilization of vegetable crops grown in greenhouses. It can be used for crops grown in soil or substrate. Nitrogen fertilizer requirements are based on the daily nitrogen uptake by the crop and take into account the mineral nitrogen in the soil at planting and the nitrogen mineralized from manure and soil organic matter. Irrigation requirements are based on estimated evapotranspiration and consider irrigation efficiency and salinity of irrigation water.	(Giménez et al. 2013).
9	INTKAM	The INTKAM crop growth model was developed to quantify the potential effects of color components and light levels on crop photosynthesis and seasonal growth and production. INTKAM has been extended to include: 1) the spectral composition of light, 2) light extinction profiles for different wavelengths, 3) the effect of color on initial light use efficiency, and 4) the maximum carboxylation capacity.	(Sánchez-Molina et al. 2015).

For the purpose of receiving precise data and a better understanding of the temperature influence on the development of crops, it is preferable to use a simulation model (Challinor et al. 2004; Lin et al. 2019). Existing present results obtained thanks to the modelling of the temperature effect on the phenology of thermophilic crops confirm that the simulation of growing conditions permits to obtain reliable data (Jones et al. 2003). For this type of research work, pepper or tomato growth models like CROPGRO can be applied, the use of which can be realized for the growing condition in the greenhouse or open field (Bacci et al. 2012; Boote et al. 2012a; Kuijpers et al. 2019).

2.7.1 Decision Support System for Agrotechnology Transfer

The Decision Support System for Agrotechnology Transfer program (DSSAT), versions 4.7.5 and 4.8, was applied to the growth models that are currently available as part of a cropping systems model (CSM) covering more than 40 crops (www.dssat.net), (Jones et al. 2003; Hoogenboom et al. 2019). From the list of fruiting vegetables, tomato and pepper were selected. DSSAT system have significant potential to improve crop performance and predict environmental impacts under different environmental management scenarios. These models also allow the identification of specific regions and limiting factors that determine the extension of thermophilic vegetable cultivation, optimizing cultivated area and economic efficiency.

2.7.2 Model CSM-CROPGRO-Tomato and CROPGRO-Pepper

The obtained results mainly focus on the possibility of using the CROPGRO growth model in DSSAT to simulate the yield parameters of tomato and pepper under changing climate conditions in the Elbe Lowland. The CROPGRO–Tomato and CROPGRO–Pepper model predicts the growth and development of the plants, leaf area index (LAI), yield, and other growth characteristics depending on soil types, weather, management practices, and variety (Potopová et al. 2023a). The algorithm used in the model is a set of differential equations that represent growth or development rates as a function of soil-plant-atmosphere dynamics. The soil-plant-atmosphere modules include competition for light and water between soil, plants, and the atmosphere. To demonstrate the performance of the CROPGRO–Tomato and CROPGRO–Pepper models for simulating growth parameters, LAI, above-ground biomass (AGB), and yield of Tornado F1, Thomas F1, and Superamy F1 have been selected. The main components of CSM-CROPGRO are included in Figure 5.

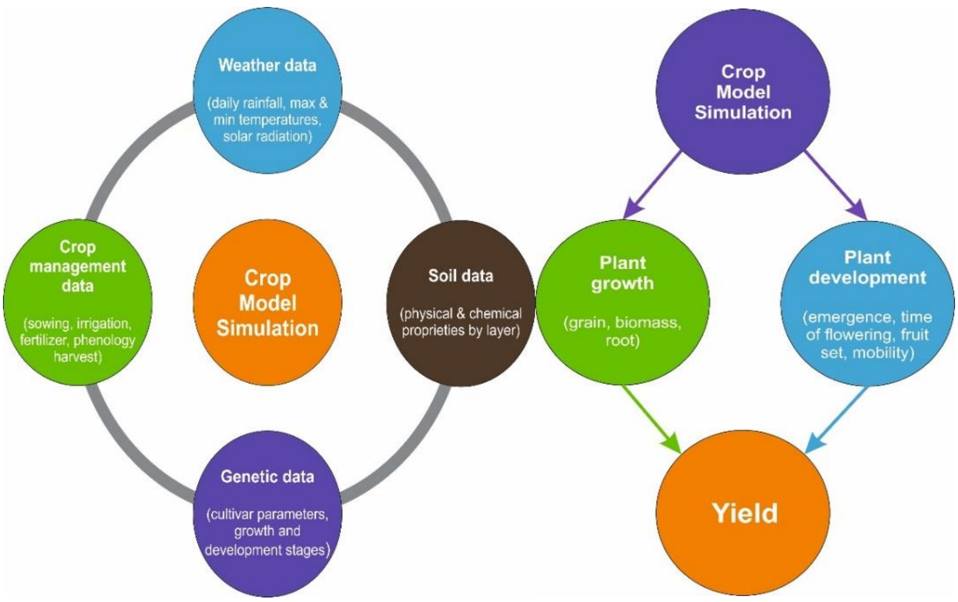

Figure 5. Components (Input and Output data) of cropping system modelling in CSM-CROPGRO (DSSAT)

By integrating these components, CSM-CROPGRO provides a complex and dynamic simulation of cropping systems, making it possible to evaluate the rentability of selected crops.

3. OBJECTIVES AND HYPOTHESES

3.1. General objective

The main objective of the dissertation thesis is to combine experimental and modelling work as tools for predicting the evolution of the production process of thermophilic vegetables and the yield of the tested varieties in the context of climate change.

3.2. Specific objectives

- Assessment of the impact of expected climate change on crop production in selected vegetable cultivation regions of the Czech Republic, especially on the Elbe lowland.
- Identification of risk meteorological factors during the growing season of vegetables and determination of their influence on the vulnerability of production in the conditions of changing climate by using climate models and the dynamic growth model.
- Assessment of an influence of weather variability in the experimental years on the possibility of achieving a stable and profitable yield of thermophilic vegetables under the climate change in the Elbe lowland.

3.3 Hypotheses

Hypothesis 1

Spring frosts, heat waves, and drought can remain the main weather risk events for growing vegetables in the future climate.

Hypothesis 2

Climate change can improve and/or exacerbate conditions for growing open-filed vegetable crops.

Hypothesis 3

The results of regional climate models and the dynamic growth model will make it possible to define the conditions for the effective cultivation of thermophilic vegetables in the Elbe lowland, outside the current borders of their profitable cultivation.

4. METHODOLOGY

The thesis methodology is focused on combining climate and growth models, including the experimental part, as tools for predicting the development of the production process of thermophilic vegetables in connection with climate change. The work consists of two scientific activities: modelling and experimental activities. The experimental activity comprise of establishing field experiments, planting, collecting, and processing plant material, monitoring plant phenology, and collecting and processing meteorological data. The second activity is based on the modelling of growth, development, and yield parameters of thermophilic vegetables. The selected growth models were used to study the relationship of the soil-atmosphere system, the results of which were tested experimentally in field conditions.

4.1 Climate data

The DSSAT-CSM required the minimum data set of daily maximum (T_{max}, °C) and minimum temperature (T_{min}, °C), global solar radiation (R_G, MJ/m^{-2}/d), and precipitation (P, mm) to simulate crop growth and development. If the global solar radiation was not recorded directly, it was converted accurately for photosynthesis and potential transpiration using the Priestley–Taylor equation (Priestley & Taylor 1972). The study connected daily weather data recorded at Poděbrady and Praha-Ruzyně climatological stations (1961–2022) from the Czech Hydrometeorological Institute ("CHMI portal" n.d.) and daily weather variables recorded by meteorological sensors in crop canopy at field farm levels for the period 2014–2022. The daily and monthly temperature and rainfall data during the growing season were obtained from the automatic meteorological station at the experimental sites (ČZU and Hanka Mochov).

The R_G was calculated by Ångström-Prescott formula (Angstrom 1924) based on the fraction of daily total atmospheric transmittance of the extra-terrestrial solar radiation (R_A), a fraction of actual (n) and potential sunshine duration (N) during the day:

$$R_G = R_A \times (A + B \times (n/N)) \qquad (1)$$

where A and B are empirical coefficients determined for the site.

4.2 Cultivar growth characteristics

The tomato varieties that are mostly cultivated in open-field conditions in the Elbe lowland are Torino F1, Strillo F1, Parto F1, Sonet F1, Galant F1, Magic F1 (Potopová et al. 2023a). In this dissertation thesis, the hybrids selected for the study were tomato Thomas F1 and Tornado F1, pepper Superamy F1, and eggplant Baikal F1.

Specific feature: High disease resistance,
Maturity: Medium,
Plant height: Indeterminate,
Fruit weight: 120-130 grams.

Figure 6. Tomato hybrid Thomas F1

Thomas F1 is early season tomato with a large red fruit (diameter of fruit is 57–67 mm;), which quickly ripens. Fruit does not crack even in adverse weather conditions. Thomas F1 is referred to as LSL (long shelf-life) with suppressed aroma formation throughout ripening. It has a high tolerance to tomato mosaic virus (ToMV) and tomato yellow leaf curl virus (TYLCV).

Specific feature: High disease resistance,
Maturity: Medium,
Plant height: Indeterminate,
Fruit weight: 110-120 grams.

Figure 7. Tomato hybrid Tornado F1

Tornado F1 is a semi-early tomato variety suitable for growing in greenhouses and open fields. It is a soft tomato with stable yields and a full tomato flavour. However, it requires a balanced moisture regime to avoid fruit cracking. Tornado F1 has been one of the most cultivated Czech tomatoes for over 20 years and is widely preferred by growers. The plant forms medium-long trusses with 7-8 fruits. During the growing season, the plant should be attached to a wooden or metal support as it can reach a height of 2.0 - 2.30 m. The most used staple is 100 × 50 cm. Gradual hand harvesting of individual fruits or harvesting of trusses can be possible in the second part of the growing season, starting in the middle of July.

Temperature requirements:

- germination: minimum 10 °C, optimum 20-25 °C.
- growth: minimum 10 °C, optimum 20-28 °C, maximum 35 °C.
- growth stops: below 10 °C.
- proper pollination within a temperature range of 15-30 °C.
- temperatures above 35 °C cause problems with fruit ripening.
- at a soil temperature below 12 °C, nitrogen mineralization is slowed down.
- pre-planting temperatures (sunny: 18-20 °C during the day, 12-14 °C at night; cloudy: 17-19 °C).
- mulching with straw at a soil temperature above 15 °C.

Water requirements:

- crop rainfall requirement: 450–500 mm.
- when pre-growing seedlings, watering with a volume of 1.5-2 l/m^2 is required (Malý 1998; Petříková 2006; Petřikova et al. 2012).

Specific feature: Big and heavy fruit,

Maturity: Early,

Plant height: Tall hybrid,

Fruit weight: 100-130 grams.

Figure 8. Pepper Superamy F1

The sweet pepper is represented by the Superamy F1 hybrid varieties Superamy F1 is an excellent hybrid of the AMY type, a very early field hybrid variety with a stable high yield and perfect health. The growth of the plants is medium, the fruits are broad needles of a cream colour intended for harvesting at technical maturity. Pepper plant seeds are sown in February, then pricked and grown at a temperature of 20 °C during the day and 16 °C at night. The temperature requirements of the Superamy F1 pepper are similar to those of the eggplant, so it is a thermoperiodically active plant. Plants are planted in open ground in the second half of May, and in order to improve temperature conditions and limit damage to plants from low temperatures, it is recommended to use non- polyester fabric bedding in the first 4-6 weeks (Malý 1998).

Temperature requirements:

- minimum temperature for cultivation is 15 °C.
- maximum temperature for cultivation is 30 °C (at higher temperatures the flowers fall off).
- optimum growing temperature is 22-25 °C during the day, 15-18 °C at night.
- germination temperature for pre-growing 25-30 °C.
- temperature after germination of pre-grown seedlings 15-17 °C during the day, 12-14 °C at night for 1 week.
- maintain a temperature of 20 °C during the day and 14–16 °C at night before planting outside.
- mulching with straw when soil temperatures are above 15 °C.

Water requirements:

- water consumption for the growing season ranges 240-400 mm.
- volume of an irrigation dose ranges 15-20 mm.
- when drip irrigation is used, 0.5 l of water per plant per day is suitable (Malý 1998; Petříková 2006; Petřikova et al. 2012).

Specific feature: High disease resistance,

Maturity: Medium,

Plant height: Middle tall,

Fruit weight: 250-350 grams.

Figure 9. Eggplant Baikal F1

For eggplant the variety Baikal F1 was selected. This variety is very early with lower temperature requirements. Under open field conditions, the Baikal F1 variety grows to a height of around 40-70 cm, while in greenhouse conditions, the eggplant can reach a height of 140 cm. The consumable part of the plant is the fruit, which is picked before ripening, as the seeds inside are very bitter when they reach botanical maturity.

Figure 10. Eggplant Baikal F1 in greenhouse condition

Eggplants require a humic, sandy loam soil with sufficient humidity. If there is a lack of humidity, the flowers fall off, and it is therefore necessary to use irrigation, mainly during the period of higher water requirements, starting in mid-July. The fruit is harvested by picking from August until the first autumn frost.

Temperature requirements:

- requires air temperatures above 20 °C and lower temperatures at night.
- pre-germinated plants are grown at 20 °C during the day and 16 °C at night.
- the plants are planted outdoors in the second half of May (non-woven polyester is used for the first 6 weeks).
- pre-growing temperatures ranges18-20 °C during the day, 12-14 °C at night.

Water requirements:

- the use of irrigation is necessary from mid-July.
- the deficiency of water causes the flowers to fall.

4.3 Characteristics of the experimental sites

The study was conducted in the Central Bohemian region (valleys of the central parts of the Czech Republic). This fruit-vegetable-producing region is characterized by the warmest and driest climatic conditions, where drought stress is often a limiting factor for crops; however, agricultural advantages of the fruiting region ensure the longest growing season and the longest frost-free period with the most productive soil conditions. Transplanting data for thermophilic vegetables grown in open fields correspond to the stable average of daily air temperature above 15°C (resulting in over

110-day season). During 1961–2022, the mean temperature of the tomato-growing season ranged from 16.5 to 18.0°C, and the total precipitation varied from 289 to 325 mm. The average maximum and minimum temperatures were 22.1 and 11.3°C, respectively (Potopová et al. 2017, 2018). Farmers usually delay the planting date of thermophilic vegetables until after 15 May in order to minimize the risk of frost damage (after this date, the risk of frost is only 10%) (Potopová V et al. 2014; Potop et al. 2014b).

In cooperation with a vegetable farm, field trials were carried out at two experimental sites (Hanka Mochov, 189 m a.s.l. and Praha-Suchdol, 287 m a.s.l) during the 2020, 2021, and 2022 growing seasons, where input data for the DSSAT - model was collected.

a) b)

Figure 11. Satellite images of the experimental localities Prague-Suchdol (a) and Mochov (b)

4.3.1 Field management of thermophilic crops

The crop management (cultivation, irrigation, fertilization, and pest protection) used in this study was based on the practices of local farmers. The experiments are a continuation of previous experiments of the Crop production department (ČZU) with various varieties with tolerance to spring frost, drought, and excess moisture in the same location. Field experiments were carried out on selected crops directly on the land of Hanka Mochov s.r.o. and the results of these experiments can be directly applied by the farmers. Promising highly resistant species and varieties of fruiting vegetables were selected. During the growing season, phenological phases were monitored, and plants were sampled to determine the dry matter content of individual organs and basic growth analytical characteristics.

Pre-growing seedlings: Sowing was done on 20th February for pepper and eggplant, and 20th March for tomato in good quality sowing medium (which was light and permeable) in mini pots with a depth of approximately 0.5-1.0 cm. After sowing, the surface was sprayed with fungicides. To reduce water evaporation, the mini pots were covered with a transparent material. The air temperature was 24.0-27.0 °C during the day and 20.0 °C at night. Plant germination rates ranged from 90 to 95% in all experimental years. As soon as the plants produced their first true leaves, they were transplanted into pots of 8 cm in diameter (Annex 9-10).

Transplanting in the open field: in all experimental years, the transplanting in the open field was started when the average daily air temperature reached 15 °C or more. Approximately 45–55-day-old seedlings were transplanted by hand into the main field, corresponding with agrotechnical requirements, by mid-May (Annex 11). The soil was ploughed to a depth of 25 cm in autumn and cultivated in spring. Nitrogen fertilization was scheduled throughout the season to deliver 170 kg/ha. The spacing maintained in the main field was 1.00 and 0.50 m between rows and plants within rows, respectively. During the growing season, only tomato suckers were pruned, and the stem was tied to the 200 cm long support. In the case of pepper and eggplant, the stem was tied to the 140 cm support.

Figure 12. The field with studied crops

Treatment: Weeds were controlled by hand; pests and diseases were completely controlled by organic treatments. Nitrogen fertilizers were applied twice. Drip irrigation (drip tube inline emitters, 2 litres/h, spaced 0.5 m) was applied according to the soil moisture once or twice per week with a dose of 15 and 20 mm. Irrigation was scheduled according to the changing needs of the plant; the young developmental stage coincided with a time with high drought frequency (mid-May and June), and the middle phase of fruit growth was a time of high water consumption (July, ~140 m^2/ha per tonne yields) (Potopová et al. 2016, 2017, 2022).

Phenology was observed weekly according to the BBCH scale (Feller C et al. 1995). Easily distinguishable visual phenological stages of the indeterminate tomato cultivars were recorded.

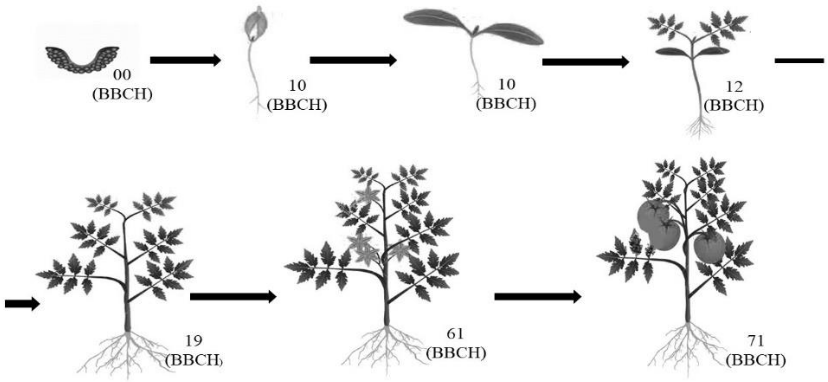

Figure 13. Phenological growth stages and BBCH-identification

Plant samples for analysis of basic physiological parameters were taken every 14 days. LAI was determined by infrared image analysis (infrared photographs with 8 Mpx. resolution). The images were processed with the analytical tool in Adobe Photoshop.

Figure 14. Photographing leaves and stems with a camera with a UV filter

The dry biomass of the plants was determined by subjecting the plant to a drying process in an oven set at a constant temperature of 105°C until all moisture content was removed. After this drying procedure, the dry biomass of the plant has been weighed.

Figure 15. The process of drying and weighing the biomass

4.4 Parameterisation of the CSM-CROPGRO system to simulate the crop growth cycle of cultivars

4.4.1 Input data sets for the model

All the data on climate, soil, crop growth, management, and yields collected in the experiments were entered in the standard DSSAT files needed for the execution of the CROPGRO-Tomato model. Experimental data sets and managing crops as well as weather and soil data for model evaluation were used. Measured and simulated growth and development of the fresh-market Thomas F1 indeterminate tomato cultivar grown under open field conditions at two locations with different soil and climate conditions were evaluated. The general cultivar information and experimental data on phenology and yield components have previously been described (Muntean et al. 2021; Potopová et al. 2023a).

Experimental data sets, crop management, weather and soil data were used to evaluate the model. The following four major groups of data sets were used to run the CROPGRO Tomato and CROPGRO Pepper models:

1) crop variety and cultivar characteristics

2 daily meteorological data

3) soil data

4) cultivation technology data set

The CROPGRO-Tomato/Pepper model integrated into the DSSAT system was calibrated and evaluated for the tomato variety Tornado F1 and the pepper variety Superamy F1 based on data measured under field conditions at the Mochov and Praha-Suchdol sites. These simulations were realized in daily steps. At the end of each day, plant and soil water, nitrogen, phosphorus, and carbon balances were updated, as well as the vegetative and reproductive stages of the crop.

4.4.2 Regional climate models in the CSM-CROPGRO system

To simulate crop growth and development, DSSAT-CSM required daily maximum (°C) and minimum temperature (°C), global solar radiation (MJ m^{-2} d^{-1}), and precipitation (mm). The DSSAT-CSM weather module was used to organise and integrate all weather data into a standard weather module format. The analysis of future climate change conditions is based on simulations using regional climate models (RCMs) prepared within the European part of the global Coordinated Regional Climate Downscaling Experiment (CORDEX), (www. cordex.org) project. Model experiments here are performed at two spatial resolutions: 0.44 degrees and 0.11 degrees (Potopová et al. 2023b). In this thesis, we focused on experiments with a resolution of 0.11 degrees forced by the RCP 8.5 scenario (Riahi et al. 2007). Climate projections for the Czech Republic do not change much by mid-century with respect to the emission scenario used (Štěpánek et al. 2019). For this reason, only the emission scenario RCP 8.5 was used. We have divided the future climate analyses into two periods: 2021-2040 and 2041-2060.

According to certification methodology of (Potopová et al. 2023a), three models selected to represent the best expected climate change with an appropriate level of uncertainty:

(1) MPI ESM LR RCA4: Represents the average of the ensemble of models (ENS_{avg}) in both air temperature and precipitation projections.

(2) MOHC HADGEM ES_RACMO22E: Model with the highest temperature but wetter than ENS_{avg}.

(3) MPI ESM LR_CLM4.8.17 (3): Model with the lowest temperature but drier than ENS_{avg}.

The following indices were modelled:

1) Sum of effective temperatures for early fruit (GDD-Tomato) is a decisive agro-climatic index for fruit ripening. This study presents an analysis of the suitability of tomato cultivation in agreement with the certification methodology of Potopová (2023) for an emphasis on temperature conditions during the growing season for the current (2001-2020) and future climate (2021-2040 and 2041-2060). The criterion for delimiting the area is based on sufficient temperature sums for effective tomato cultivation (GDD). The algorithm for calculating the GDD from planting to technical maturity under the Czech Republic conditions was included in the study of Potopová.

2) Number of days with effective temperatures for tomato. The number of days needed for the fruit to ripen to reach technical maturity. The higher the number of days with effective temperatures, the greater the possibility of ripening the fruit for early, medium, and late varieties (i.e., the higher the number of days with effective temperatures, the higher the profitability of cultivation).

3) Number of days with spring frosts according to their intensity. The agrometeorological risk of frost damage to production depends on the critical threshold of minimum air temperature, which varies for different vegetable species and their developmental stages. Therefore, the daily minimum air temperature during the vegetable planting season was used to assess the risk. Limits of the critical minimum daily temperature intervals were established considering the physiological requirements of the different species:

mild frost: t_{min} 0.0 to -1.1 °C

moderate frost: t_{min} -1.2 to -2.2 °C

severe frost: t_{min} < -2.2 °C.

4.5 Soil SBuild module in CSM-CROPGRO

Specific soil parameters required for the model input, such as a lower limit, drained upper limit and saturation, drainage coefficient, and runoff curve number, were estimated from the measurement of the soil profile. The soil data from the experimental sites were collected from the field based on the soil layer depths (10 cm each up to 90 cm) by using the soil standard sampling materials and keeping the soil samples air-tight zip bags. The physical and chemical analyses of sampled soil were performed in the soil analysis laboratory. The soil input data sets in the SBuild module included percent of clay, silt, sand, and organic carbon, pH, cation exchange capacity, slope, albedo, colour, drainage, the drained upper limit (DUL), total soil nitrogen, lower limit (LL), saturated water content (SAT), hydraulic conductivity, bulk density, root growth factor (SRGF) and soil fertility factor (SLPF) (Jones et al. 2003). The measured soil data from both Mochov and Praha-Suchdol sites are presented in Table 2. The soil profiles for Mochov and Praha-Suchdol sites were characterized as Haplic Chernozems and Sandy Loamy Cambisol, respectively. These are fertile soils with neutral reaction, higher content of clay particles, higher cation exchange capacity and low soil water retention capacity.

Table 2. Soil texture and structure dataset from experimental sites for the CSM-CROPGRO-Tomato/Pepper models

Layer depth Soil (cm)	Clay (%)	Dust (%)	Sand (%)	SLOC (%)	SLHV	CEC (cmol kg^{-1})	SLNI (%)	LL (cm^3 cm^{-3})	DUL (cm^3 cm^{-3})	BD (g cm^{-3})
Mochov										
0–10	23.1	57.6	17.2	1.58	5.2	20.1	0.11	0.18	0.39	1.31
10–20	24.2	58.2	18.6	1.57	5.1	20.2	0.13	0.19	0.40	1.32
20–30	22.7	59.6	17.6	1.59	5.4	20.4	0.10	0.18	0.39	1.33
30–40	23.4	59.1	16.6	1.98	5.7	20.1	0.10	0.20	0.41	1.39
40–50	24.2	59.3	16.7	1.97	5.8	19.7	0.10	0.21	0.41	1.35
50–60	23.8	61.1	16.0	1.83	6.1	19.8	0.12	0.19	0.40	1.38
60–70	22.4	58.9	16.9	1.48	6.3	13.5	0.13	0.18	6	1.43
70–80	23.3	60.1	17.5	1.45	6.6	13.3	0.12	0.17	0.37	1.42
80–90	21.5	61.2	18.3	1.43	6.5	12.2	0.12	0.19	0.38	1.39
Prague -Suchdol										
0–10	34.3	51.3	14.7	2.29	7.8	23.6	0.13	0.24	0.45	1.62
10–20	34.7	50.4	14.8	2.27	7.9	23.9	0.11	0.25	0.47	1.61
20–30	34.9	49.8	15.3	2.17	7.5	23.5	0.14	0.26	0.46	1.58
30–40	35.4	49.7	15.4	2.45	7.6	23.6	0.15	0.27	0.45	1.61
40–50	35.6	49.5	15.3	2.42	7.8	23,5	0.14	0.28	0.48	1.62
50–60	35.5	48.8	15.6	2.39	7.4	23.4	0.10	0.27	0.46	1.59
60–70	35.6	49.4	15.1	2.45	7.5	23.2	0.12	0.29	0.48	1.57
70–80	35.8	49.2	15.2	2.43	7.6	23.5	0.14	0.27	0.49	1.54
80–90	35.9	48.9	153	2.38	7.7	23.6	0.13	0.26	0.47	1.53

4.6 Crop management in DSSAT CSM-CROPGRO

XBuild (Crop Management Module) is an experimental tool for entering experimental data in DSSAT CSM-CROPGRO. It allows the users to add their own experimental data to the model and test crop performance under different environmental and management conditions. A set of experimental crop management data was developed for the experiment conducted in 2020, 2021, and 2022. The crop management data included growth characteristics of Thomas F1, Tornado F1 and, Superamy F1 varieties: planting date, emergence date, transplanting date, number of plants, plant height, leaf area measurements, flowering date, maturity date, harvest date, and yield at the two experimental sites (Table 3).

Table 3. Selected crop management practices during the calibration and verification period

Year	**Date of planting**		**Flowering date (DAP)**		**Date of first fruit set (DAP)**		**Date of first seed set (DAP)**		**Harvest maturity date (DAP)**		**Leaf area index (m^2m^{-2})**	
	MO	**SU**	**MO**	**SU**	**MO**	**SU**	**MO**	**SU**	**MO**	**SU**	**MO**	**SU**
2020	20.05	21.05	10	12	20	22	31	32	129	134	1.61	2.05
2021	24.05	25.05	14	15	24	26	36	37	135	137	2.73	2.27
2022	10.05	13.05	8	11	22	24	32	33	125	130	1.71	1.64

*MO: Mochov; SU: Prague-Suchdol, DAP: days after planting

Figure 16. Tomato and pepper at the stage of flower formation and flowering (first part of June)

Approximately 65-90 days following germination, tomato plants initiate the flowering stage. In the case of peppers, this stage occurs earlier, around 55-65 days after germination.

Figure 17. Tomato and pepper at fruit set stage (July)

Figure 18. Tomato and pepper at fruit ripening stage (end of July and first part of August)

4.7 Calibration of cultivar growth coefficients in the CROPGRO-TOMATO and CROPGRO-Pepper Models

Growth models require large amounts of input data and experimental information for their calibration and calculations. The CROPGRO-Tomato model required calibration of the growth coefficients in the cultivar file because a new variety was used in DSSAT. These coefficients describe the duration of the developmental growth stages of a particular cultivar. For the calibration and evaluation of the DSSAT-CROPGRO-Tomato model, a dataset on the management of tomato plants of the variety

Thomas F1 from the experimental site Mochov in the years 2014-2020 was used. The reference calibrated parameters of tomato under field conditions in the Elbe lowland were set according to the hybrid variety Thomas F1. Parameters adjusted for the tomato variety Tornado F1 were comparable to the set for the variety Thomas F1. The calibrated values of variety and ecotype parameters for the study sites are presented in Table 4.

Different sets of phenological data (plant emergence date, planting date, anthesis date, date of first flowering, date of fruit set, date of technical maturity) and yield attributes (e.g., final yield, aboveground biomass, maximum leaf area during the season) were used to estimate sets of growth coefficients specific to the hybrid varieties Tornado F1 and Superamy F1.

Table 4. Parameters adjusted of Thomas F1 variety during the CROPGRO-Tomato model calibration.

Parameter	**Definition**	**Testing range**	**Calibrated values**
EM-FL	Time between plant emergence and flower appearance (GDD)	8.0–24.5	10.0
FL-SH	Time between first flower and first pod (GDD)	2.3–4.5	2.4
FL-SD	Time between first flower and first seed (GDD)	18.5–25.5	23
SD-PM	Time between first seed and physiological maturity (GDD)	34.0–46.0	45
FL-LF	Time between first flower and end of leaf expansion (GDD)	34.0–53.0	41
LFMAX	Max. leaf photosynthesis rate at 30°C, 350 vpm CO_2, and high light (mg CO_2 m^{-2} s^{-1})	1.21–1.37	1.35
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm^2 g^{-1})	251.0–351.0	301
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell	0.51–0.79	0.62
SFDUR	Seed filling duration for pod cohort at standard growth conditions (GDD)	24.1–27.2	25.0
PODUR	Time required for cultivar to reach final pod load under optimal conditions (GDD)	51.0–57.0	53.0

PL-EM	Time between planting and emergence (GDD)	10.0–15.0	11.0
EM-V1	Time required from emergence to first true leaf (GDD)	21.0–26.0	23.0
PODUR	Time required for cultivar to reach final pod load under optimal conditions (GDD)	52.0–58.0	54.0
FL-VS	Time from first flower to last leaf on main stem (GDD)	22.4–26.5	23.5

*GDD: thermal days

The DSSAT-CROPGRO-Pepper model was calibrated and evaluated using a dataset from the experimental site in Mochov, encompassing the management practices applied to pepper plants of the Superamy F1 variety during the years 2020 to 2022.

Table 5. Parameters adjusted of Superamy F1 variety during the CROPGRO-Pepper model calibration.

Parameter	**Definition**	**Testing range**	**Calibrated values**
EM-FL	Time between plant emergence and flower appearance (GDD)	10.0–22.5	12.0
FL-SH	Time between first flower and first pod (GDD)	1.3–3.5	2.4
FL-SD	Time between first flower and first seed (GDD)	19.5–24.5	21
SD-PM	Time between first seed and physiological maturity (GDD)	31.0–44.0	40
FL-LF	Time between first flower and end of leaf expansion (GDD)	30.0–50.0	38
LFMAX	Max. leaf photosynthesis rate at 30°C, 350 vpm CO_2, and high light (mg CO_2 m^{-2} s^{-1})	0.79–0.91	0.83
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm^2 g^{-1})	111.0–251.0	203
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell	0.31–0.59	0.42
SFDUR	Seed filling duration for pod cohort at standard growth conditions (GDD)	21.1–25.2	23.0
PODUR	Time required for cultivar to reach final pod load under optimal conditions (GDD)	49.0–55.0	51.0

PL-EM	Time between planting and emergence (GDD)	9.0–14.0	11.0
EM-V1	Time required from emergence to first true leaf (GDD)	20.0–25.0	22.0
PODUR	Time required for cultivar to reach final pod load under optimal conditions (GDD)	48.0–55.0	51.0
FL-VS	Time from first flower to last leaf on main stem (GDD)	20.4–25.5	22.5

*GDD: thermal days

In order to refine the simulation of growth and yield characteristics and their dependence on temperature, the cardinal temperature (i.e., how temperature affects the vegetative and generative growth phase of tomato, photosynthesis, fruit set, and the rate of growth and development of individual fruits) had to be adjusted in the model. Cardinal temperatures (T_b - threshold temperature, T_{opt1} and T_{opt2} - minimum and maximum temperatures at which the rate of the physiological process is highest, T_{max} - maximum temperature of the physiological process) and lethal temperatures (Tl_{min} and Tl_{max} - lethal minimum and lethal maximum) describe the essential temperature requirements of plant production. The ideal conditions for crop growth and development are in the interval T_{opt1} and T_{opt2}. Newly calibrated values of crop development parameters and crop coefficients for the CROPGRO-Tomato and CROPGRO-Pepper models' version 4.8 were used. The parameters related to the crop coefficients for the CROPGRO-Tomato and CROPGRO-Pepper models are shown in Table 6.

Table 6. Cardinal temperatures of the developmental stages of the tomato and pepper in DSSAT crop model.

Physiological process and phase BBCH	**Temperature requirements (cardinal temperatures) [°C]**			
	T_b	T_{opt1}	T_{opt2}	T_{max}
Tomato				
Growth rate of leaf area / 10–29	8.2–10.5	21.0	25.0	32.0
Rate of formation of flower organs / 51–69	9.1–10.1	22.0	26.0	33.0
Rate of fruit formation and ripening / 71–89	13.0–16.0	24.0	30.0	36.0
Pepper				
Growth rate of leaf area / 10–29	9.2–11.5	22.0	26.0	33.0
Rate of formation of flower organs / 51–69	12.1–15.1	21.0	26.0	31.0
Rate of fruit formation and ripening / 71–89	15.0–17.0	22.0	29.0	35.0

*T_b: threshold temperature at which the physiological process ceases; T_{opt1}: temperature minimum at which the rate of the physiological process is highest; T_{opt2}: the temperature maximum at which the rate of the physiological process is highest; T_{max}: the maximum temperature of the physiological process.

4.7.1 Evaluation of the model

Experimental information such as planting date, plant population per square meter, planning depth, row spacing and harvesting date was used as crop management practices. At the same time, data on plant phenological stages such as emergence, anthesis, LAI and AGB based on days after planting, pod formation, physiological maturity and harvest maturity were also used in the calibration process. The AGB values were expressed in dry matter for the calibration and evaluation of the model. Since the Thomas F1 variety of tomato was not included in the DSSAT cultivar database, it was added as a new cultivar into the database and its parameters were populated based on the field experimental data set. We applied the newly calibrated values of the ecotype file and cultivar coefficients for LAI and AGB (Potopová et al. 2023a). The simulated dates and values of the LAI and AGB were compared with the observed dates. The simulated dates and values varied in different years due to the differences in planting dates, photothermal duration, precipitation, and weather-related parameters during the tomato-growing seasons. Performance statistics indicator used in this study was root mean square error (RMSE), which was calculated using equation (2). A lower RMSE value indicates fewer differences between the simulated and observed values.

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

where Y_i = observed value, $\hat{Y}_i$ = simulated value, $\overline{Y}_i$ = average of simulated value, $\overline{Y}$ = average of observed value, n = number of observations and n – (k + 1) = degrees of freedom.

5. RESULTS

5.1 Compound weather events during the growth seasons of the three experimental years

This section focuses on the quantification of compound events (CEs) occurrences from transplanting to harvest of the cultivars. An overview of the frequency of CEs (hot, hot-dry, and hot-wet days) during the growing season at two locations is shown in studies (Muntean et al. 2021; Potopová et al. 2023a)

Table 7. Evaluation of the temperature and rainfall compound events for each month of the vegetables growing season (May–September) during each experimental year

Praha	May	June	July	August	September
		2020			
Δt, °C	-1.3	0.7	0.9	2.4	1.2
P, %	91	160	56	136	139
Δt, °C – P, % category	normal, normal	normal, moderate wet	normal, normal	severe warm, moderate wet	moderate warm, moderate wet
		2021			
Δt, °C	-2.4	1.6	-0.2	-2.4	0.9
P, %	175	132	97	117	39
Δt, °C – P, % category	moderate cold, moderate wet	moderate warm, moderate wet	moderate cold, normal	severe cold, normal	normal, moderate drought
		2022			
Δt, °C	2.2	2.3	-4	1	-1.7
P, %	57	256.1	100.3	92.6	101.9
Δt, °C – P, % category	moderate warm, moderate drought	severe warm, extreme wet	extreme cold, normal	normal, normal	moderate cold, normal

Mochov	May	June	July	August	September
		2020			
Δt, °C	-1.9	-0.5	-1.3	0.4	-0.1
P, %	108.1	106.1	70.6	100.5	95.5
Δt, °C – P, % category	normal, normal	normal, normal	moderate cold, normal	normal, normal	normal, normal
		2021			
Δt, °C	-2.3	1.5	-0.2	-2.2	0.6
P, %	139	79.4	134	99.7	21.9
Δt, °C – P, % category	moderat cold, normal	moderate warm, normal	moderat cold, moderat wet	severe cold, normal	normal, severe drought
		2022			
Δt, °C	0.9	1.4	-0.8	0.7	-2.9
P, %	76.9	97.4	53.7	101.4	110.7
Δt, °C – P, % category	normal, normal	moderate warm, normal	moderat cold, moderat drought	normal, normal	severe cold, normal

Note: Δt, deviations of the mean monthly air temperature from the long-term mean; °C; P, %, percentage of monthly long-term precipitations; °C–P, %, coupling of anomalies of temperature–precipitation patterns.

The growing season of 2020 can be characterized as normal for Mochov site with an exception for July (Table 7). The transplanting of the studied crops in the open field took place on the 20 May due to the low night temperatures. For Suchdol site, the air temperature in the first three months was normal. August was severely warm, and September was moderately warm. In August and September was moderate to severe warm, which contributed to increasing the harvest season by 10 days.

The growing season in 2021 was cold and wet, while 2022 was warm with alternating dry periods and normal rainfall. At both research sites, normal weather conditions occurred in 2021 for approximately 60% of the total growing season from May to September. At the time of transplanting in 2021, which took place on 25 May, there was a slightly cold spell at both sites. During the flowering and fruiting period, the temperature deviation from normal ranged from +1.6 °C (slightly warm period) to -0.2 °C (cold period) at both experimental sites. The ripening period was cooler than normal (-2.2 °C), but the harvest period was warm and dry. Based on the records of the 2021 field trial, the following negative effects can be noted: two weeks of delays in planting; a very cold and wet start to the growing season. These negative factors slowed down the growth and development of the generative organs in tomatoes, peppers, and eggplants.

In the 2022 growing season, due to high temperatures in May, the transplanting of seedlings into the field took place earlier on 13 May. Moderate to severe warm weather prevailed at both experimental sites for approximately 40 % of the total growing season. May was moderately warm–dry. The flowering period at Prague-Suchdol was very warm–extremely wet (256 % of normal rainfall; twice rainfall norm fell in a short period of time). In Mochov, flowering took place in warm and normal rainfall conditions. The second part of the growing season at both sites alternated between a cold–dry July, a normal August, and a cold September. Although the growing season for studied crops was generally shorter in 2022, the sum of effective temperatures for the maturation of warm-season vegetables was higher in contrast to the previous year.

During the three experimental years, the most optimal growing season for the growth and development of the studied plants was observed in the year 2020, coinciding with the highest recorded yields per hectare.

5.2 Experimental crop production of tomato, pepper, and eggplant

The obtained yield per hectare of studied crops was higher in Mochov than in Prague-Suchdol during the whole three experimental years (Figure 19).

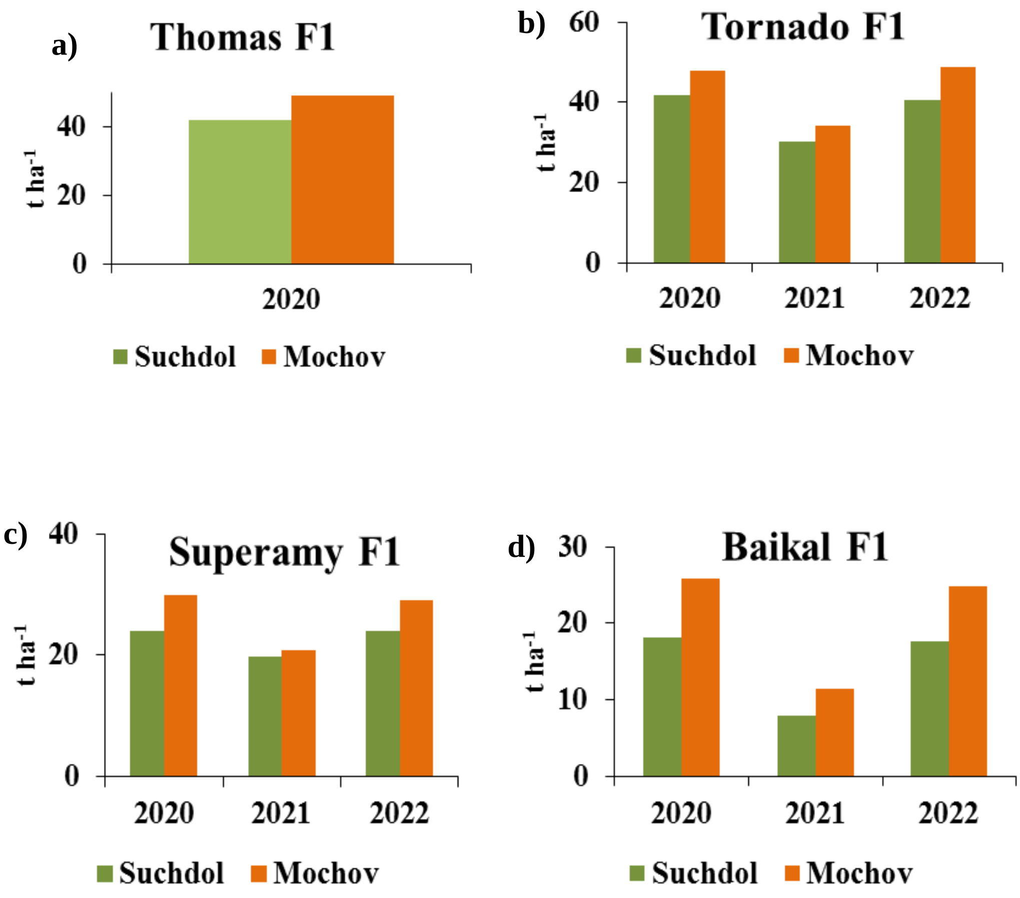

Figure 19. The total yield of studied crops during the three experimental years

Thomas F1 and Tornado F1 are indeterminate varieties with 10-11 inflorescence per plant, of which only 6-7 fruit trusses reach maturity in warm years. Due to the low temperatures in 2021, the growth, development, and ripening of tomato fruit were very slow, with only the first 4 fruit trusses in Suchdol and 5 fruit trusses in Mochov managing to ripen. The harvest obtained under field conditions in 2020 of the Thomas F1 variety in Suchdol was 41.9 t ha^{-1} and in Mochov 49.1 t ha^{-1} (Figure19 a). In 2021, the total yield of the Tornado F1 variety was 30.3 t ha^{-1} in Suchdol and 34.2 t ha^{-1} in Mochov (Figure 19 b). The most significant amount of fruit was harvested on the picking dates of 25 August to 6 September. The 2020 and 2022 years were warmer than 2021, that which impacted tomato yields and other thermophilic crops. The obtained yield of Tornado F1 in 2020 was 41,7 t ha^{-1} at Suchdol and 47,9 t ha^{-1} at Mochov. In the case of 2022, tomato yield reached 40,5 t ha^{-1} at Suchdol and 48,7 t ha^{-1} at Mochov. The highest harvest was achieved in the period from 16 August to 25 August, with a slight decrease towards the end of the season (Anex 4).

In 2021, the pepper yield was lower than the growing seasons of 2020 and 2022 with 20.7 t ha^{-1} at Mochov and 19.7 t ha^{-1} in Suchdol. The highest pepper yields in 2021 were obtained between 2 and 11 August and between 21 August and 2 September. The pepper yield in 2020 was 24,1 t ha^{-1} for Suchdol and 29,9 t ha^{-1} for Mochov. In 2022, the pepper yield was 23.9 t ha^{-1} in Mochov and 29.1 t ha^{-1} in Suchdol (Figure 19 c). Due to favourable growing seasons characterized by warm and dry conditions between 2020 and 2022, substantial pepper yields were attained early beginning of the harvest period (20 July to 31 July), leading to increased profitability for growers who could obtain higher market prices. The peak yields in 2020 and 2022 were observed between 11 August and 1st September (Annex 5).

The eggplants harvest obtained under field conditions in 2020 of the Baikal F1 cultivar at Suchdol was 18.2 t ha^{-1} and in Mochov 24.9 t ha^{-1} (Figure 19d). In 2021, the eggplants reached 7.9 t ha^{-1} at Suchdol and 11.5 t ha^{-1} at Mochov. The eggplants harvest in 2022 was 17.7 t ha^{-1} in Suchdol and 24.9 t ha^{-1} in Mochov. The highest yields were harvested in the second part of August for all three experimental years (Annex 6).

Despite the relatively moderate yield per hectare observed under the current climate conditions in Elbe lowland, eggplant continues to be regarded as a promising crop with potential for farmers in the coming years.

Figure 20. Pepper and eggplant at the end of the field experiment

Summarization of associated meteorological phenomena during the crop growing season:

1) The dominant type of adverse situation in the warmest area of the Elbe Lowland region for the production of studied crops is the occurrence of stress from low temperatures and an increase in the duration of the wet season in sensitive growth stages, which leads to rapid fruit damage and yield drops.
2) When the number of dry days exceeded the set limit for the frequency of phenomena, the yield was reduced. If this phenomenon occurs in September, it promotes fruit ripening and has a positive effect on the yield (increase in yield by 21%).
3) An even greater yield loss was caused by alternating extremely wet and dry periods with the longest duration at the key stage of fruit ripening when yield dropped by 48%. However, the largest share of yield losses occurred during heavy rainfall in July and August.

4) Temperature stress occurred mainly in the month of July and led to a 33% reduction in yield. Because high temperatures in tomatoes cause disturbances in the formation of flowers and worsen pollination.

5.3 Monitoring the experimental dry weight of above-ground biomass of various types of thermophilic crops.

The set of experimental dry above-ground biomass weights of the plants consisted of three parts: leaves, stems, and generative parts (Tables 8-13). The generative part includes the following stages: flower formation at the phenological growth stage BBCH 51, flowering (BBCH 61), fruit formation (BBCH 71), and fruit ripening (BBCH 81).

Evolution of dry above-ground biomass of Thomas F1 in the 2020 growing season is shown in Table 8. The total allocation of dry biomass in Thomas F1 cultivar was distributed among different plant components as follows: at Mochov, 31.0% was allocated to leaves, 14.8% to stems, and 54.1% to generative (reproductive) parts. At Suchdol, the allocation percentages were 30.1% for leaves, 14.4% for stems, and 55.4% for generative parts. The temperature and precipitation extremes were also reflected in the development of the above-ground biomass of tomato and pepper plants. Leaf stalk biomass weights for both Tornado F1 and Superamy F1 showed higher values under cold temperatures and wet conditions in 2021 compared to warm and dry conditions in 2022. However, generative organs showed a decreasing trend in 2021 compared to 2022. The decisive risk factor for the formation of the generative parts of tomatoes in 2021 was thermal stress caused by large differences between night and day air temperatures during the flowering phase. In 2022, low night temperatures and heavy rains in the second half of July were an unfavourable factors. The amount of biomass obtained from leaves in 2021 was higher compared to 2022. Cooler conditions contributed to the increase of biomass, and due to low temperatures and low light intensity, the generative parts did not develop or even broke. The plant thus redirected energy and nutrients to leaf development.

Table 8. Evolution of dry above-ground biomass of Thomas F1 in the 2020 growing season

Date	**Measurement number**	**Aboveground biomass (dry weight per plant, g)**					
		Mochov			**Suchdol**		
		Leaf	**Stem**	**Gener.**	**Leaf**	**Stem**	**Gener.**
21.05.2020	0	0.21	0.1	0	0.93	0.1	0
05.06.2020	1	2.66	1.61	0.2	2.97	0.78	0.2
19.06.2020	2	20.7	7.17	2.5	7.42	1.95	2.5
01.07.2020	3	78.2	24.56	17	24.66	8.5	17
14.07.2020	4	85.5	29.79	150	45.74	19.33	150
27.07.2020	5	101.2	49.36	183.31	66.33	30.2	153.31
11.08.2020	6	127.4	62.01	266.01	88.9	38.93	166.01
25.08.2020	7	123.7	63.04	244.4	101.16	49.74	144.4
09.09.2020	8	93.4	64.13	241.02	82.8	52.19	141.02
	Total	632.97	301.77	1104.4	420.91	201.72	774.4

Table 9. Evolution of dry above-ground biomass of Tornado F1 in the 2020 growing season

Date	**Measurement number**	**Aboveground biomass (dry weight per plant. g)**					
		Mochov			**Suchdol**		
		Leaf	**Stem**	**Gener.**	**Leaf**	**Stem**	**Gener.**
21.05.2020	0	0.93	0.2	0	0.2	0.05	0
05.06.2020	1	7.46	1.64	0.4	4.1	0.6	0
19.06.2020	2	22.1	7.22	2.58	8.3	1.9	1.1
01.07.2020	3	60.52	25.02	16.94	48.6	5.9	13.2
14.07.2020	4	65.68	27.48	139.68	57.1	31.1	136.2
27.07.2020	5	94.25	49.05	180.96	62.9	32.8	148.6
11.08.2020	6	129.13	62.96	261.09	77.8	38.8	167.6
25.08.2020	7	120.12	64.01	242.46	97.1	49.2	152.7
09.09.2020	8	80.93	65.02	238.12	82.8	51.9	144.8
	Total	581.12	302.6	1082.23	438.9	212.25	764.2

In the case of the mass of generative parts, both Tornado F1 and Superamy F1 showed higher values under warm and normal precipitation conditions in 2022 than under cold temperature and wet conditions in 2021 for both experimental sites. The weight of the generative parts of Tornado F1 at the Mochov location in 2022 increased by 43% (1030.9 717.6 g [dm=dry matter] plant^{-1}) compared to 2021 (717.6 g [dm] plant $^{-1}$). While at the Suchdol location it increased by approx. 53% compared to 2021. For the Superama F1, the weight of the generative parts increased by 8.7% at the Mochov location and by 24.5% at the Suchdol location.

Table 10. Evolution of dry above-ground biomass of Superamy F1 in the 2020 growing season

Date	Measurement number	Aboveground biomass (dry weight per plant, g)					
		Mochov			Suchdol		
		Leaf	Stem	Gener.	Leaf	Stem	Gener.
21.05.2020	0	0.77	0.5	0	0.77	0.5	0
05.06.2020	1	1.2	0.6	0	0.99	0.7	0
19.06.2020	2	4.4	4.7	0.25	3.9	4.8	0.24
01.07.2020	3	9.2	7.5	3.3	10.8	7.4	3.1
14.07.2020	4	17.5	12.6	6.2	15.1	11.9	5.4
27.07.2020	5	30.6	19.1	30.7	29.3	18.3	29.8
11.08.2020	6	32.8	27.5	45.9	30.9	26.1	34.2
25.08.2020	7	35.5	31.2	48.8	34.1	30.8	46.9
09.09.2020	8	37.7	32.9	42.6	35.2	31.5	38.1
	Total	169.67	136.6	177.75	161.16	132	157.74

Table 11. Evolution of dry weight of above-ground biomass of Baikal F1 in the 2020 growing season.

Date	Measurement number	Aboveground biomass (dry weight per plant. g)					
		Mochov			Suchdol		
		Leaf	Stem	Gener.	Leaf	Stem	Gener.
21.05.2020	0	0.79	0.11	0	0.79	0.1	0.1
05.06.2020	1	2.22	0.87	0	2.52	0.78	0.78
19.06.2020	2	5.35	2.73	0.73	5.77	2.18	2.18
01.07.2020	3	17.86	19.31	1.31	19.05	6.03	6.03
14.07.2020	4	22.74	20.3	7.03	22.65	6.64	6.64
27.07.2020	5	48.07	35.89	27.99	31.98	6.67	6.67
11.08.2020	6	66.11	55.15	52.05	39.58	20.69	20.69
25.08.2020	7	72.18	60.24	61.91	48.85	41.19	41.19
09.09.2020	8	90.15	70.21	48.51	58.65	55.16	35.16
	Total	325.47	264.81	199.53	229.84	139.44	119.44

The total distribution of Baikal F1 cultivar dry biomass during 2020 at Mochov resulted in an allocation of 41.2% to leaves, 33.5% to stems, and 25.3% to generative parts. At Suchdol, the allocation percentages were 47.0% for leaves, 28.5% for stems, and 24.4% for generative parts. In 2021 at Mochov, 40.4% was allocated to leaves, 19.3% to stems, and 40.3% to generative parts. At Suchdol, the allocation percentages were 37.0% for leaves, 18.4% for stems, and 44.5% for generative parts. The total distribution of dry biomass in Mochov resulted in an allocation of 41.8% to leaves, 35.3% to stems, and 22.9% to generative parts. At Suchdol, the allocation percentages were 45.7% for leaves, 29.6% for stems, and 24.7% for generative parts. These percentages represent the relative contributions of biomass from each component, providing insights into the biomass allocation patterns of the Tornado F1, Superamy F1 and Baikal F1 cultivars in the respective locations.

Table 12. Evolution of the dry weight of above-ground biomass of Tornado F1 in the 2021 growing season

Date	Measurement number	Aboveground biomass (dry weight per plant, g)					
		Mochov			Suchdol		
		Leaf	Stem	Gener.	Leaf	Stem	Gener.
25.05.2021	0	2.2	0.2	0	2.2	0.2	0
10.06.2021	1	6.2	2.6	0.1	6.0	4.0	0
28.06.2021	2	17.8	7.0	0.8	19.0	8.6	0.2
13.07.2021	3	87.2	27.4	20.4	53.6	20.4	1.9
26.07.2021	4	97.6	47.2	76.3	54.9	20.9	24.2
09.08.2021	5	103.4	62.9	135.1	59.8	33.1	64.2
23.08.2021	6	157.2	64.4	175.5	61.6	37.1	145.7
05.09.2021	7	141.9	65.8	188.5	80.4	40.1	132.9
18.09.2021	8	105.2	65.9	120.9	75.7	41.5	128.2
	Total	718.7	343.4	717.6	413.2	205.9	497.3

Table 13. Evolution of the dry weight of above-ground biomass of Superamy F1 in the 2021 growing season

Date	Measurement number	Aboveground biomass (dry weight per plant, g)					
		Mochov			Suchdol		
		Leaf	Stem	Gener.	Leaf	Stem	Gener.
25.05.2021	0	0.8	0.04	0	0.8	0.04	0
10.06.2021	1	1.4	0.6	0	1.2	0.6	0
28.06.2021	2	4.9	4.6	0.2	1.8	0.7	0.1
13.07.2021	3	11.4	6.6	2.0	6.6	2.8	2.4
26.07.2021	4	23.4	26.1	20.1	7.0	3.6	19.9
09.08.2021	5	36.9	31.6	40.4	14.8	10.1	35.6
23.08.2021	6	41.9	40.3	42.1	18.5	10.6	25.2
05.09.2021	7	54.1	60.6	43.6	19.2	11.1	27.4
18.09.2021	8	55.2	61.4	12.8	19.9	11.9	15.2
	Total	230.0	231.8	161.2	89.8	51.4	125.8

Table 14. Evolution of dry weight of above-ground biomass of Baikal F1 in the 2021 growing season

Date	Measurement number	Aboveground biomass (dry weight per plant, g)					
		Mochov			Suchdol		
		Leaf	Stem	Gener.	Leaf	Stem	Gener.
25.05.2021	0	1.6	0.19	0	1.6	0.09	0
10.06.2021	1	2.4	0.61	0	3.1	0.72	0
28.06.2021	2	5.6	2.21	0.41	5.4	1.85	0
13.07.2021	3	11.2	13.8	1.01	18.2	6.2	0.8
26.07.2021	4	31.8	21.08	10.8	20.2	10.2	0.6
09.08.2021	5	46.9	36.1	17.8	36.2	29.1	18.9
23.08.2021	6	55.1	45.2	20.2	49.4	42.2	24.8
05.09.2021	7	85.2	52.9	29.3	52.1	49.2	26.1
18.09.2021	8	93.2	62.8	23.1	61.8	54.1	21.4
	Total	333.0	234.89	102.62	248.0	193.66	92.6

Table 15. Evolution of the dry weight of above-ground biomass of Tornado F1 in the 2022 growing season

Date	Measurement number	Aboveground biomass (dry weight per plant, g)					
		Mochov			Suchdol		
		Leaf	Stem	Gener.	Leaf	Stem	Gener.
13.05.2022	0	0.95	0.05	0	0.93	0.1	0
01.06.2022	1	5.97	0.6	0.4	2.97	0.78	0.3
16.06.2022	2	17.42	6.6	33.8	7.42	1.95	2.4
07.07.2022	3	44.66	23.1	155.1	24.66	8.5	16.98
22.07.2022	4	65.74	29.8	163.4	45.74	19.33	142.2
08.08.2022	5	86.33	48.3	208.1	66.33	30.2	154.19
22.08.2022	6	112.9	63.5	207.5	88.9	38.93	165.68
06.09.2022	7	121.16	64.1	156.3	101.16	49.74	142.98
21.09.2022	8	92.8	64.4	106.3	82.8	52.19	138.17
	Total	547.93	300.45	1030.9	420.91	201.72	762.9

Table 16. Evolution of dry weight of above-ground biomass of Superamy F1 in the 2022 growing season

Date	Measurement number	Aboveground biomass (g dry weight per plant)					
		Mochov			Suchdol		
		Leaf	Stem	Gener.	Leaf	Stem	Gener.
13.05.2022	0	0.7	0.4	0	0.7	0.4	0
1.06.2022	1	1.4	0.7	0	0.9	0.1	0
16.06.2022	2	6.3	3.1	0.3	3.4	1.8	0.3
07.07.2022	3	12.1	8.3	5.3	9.7	2.5	0.5
22.07.2022	4	16.6	12.5	6.3	18.1	5.3	2.1
08.08.2022	5	25.1	16.4	41.8	32.4	15.2	3.8
22.08.2022	6	32.1	22.4	37.7	34.6	20.9	22.1
06.09.2022	7	33.3	22.9	52.7	34.4	20.9	35.1
21.09.2022	8	29.7	21.4	30.8	385	23.4	37.7
	Total	157.3	108.1	174.9	172.7	90.5	101.6

Table 17. Evolution of dry weight of above-ground biomass of Baikal F1 in the 2022 growing season

Date	**Measurement number**	**Aboveground biomass (g dry weight per plant)**					
		Mochov			**Suchdol**		
		Leaf	**Stem**	**Gener.**	**Leaf**	**Stem**	**Gener.**
13.05.2022	0	0.31	0.25	0	0.31	0.25	0
01.06.2022	1	0.66	0.77	0	1.36	0.32	0
16.06.2022	2	0.84	2.15	0.29	2.56	0.41	0
07.07.2022	3	12.52	14.74	0.08	19.1	5.61	0.8
22.07.2022	4	31.45	24.01	7.04	21.45	8.76	5.14
08.08.2022	5	45.59	36.66	22.94	28.24	15.61	15.29
22.08.2022	6	61.56	50.08	43.73	39.22	25.31	22.78
06.09.2022	7	74.48	64.6	58.72	47.48	34.89	40.59
21.09.2022	8	87.89	73.45	40.15	56.56	48.94	32.12
	Total	315.3	266.71	172.95	216.28	140.1	116.72

Summary of experimental results:

1) Thermophilic vegetables at the Suchdol compared to the Mochov site had lower values of dry above-ground biomass and the slower and later onset of generative developmental stages.
2) The distribution of dry matter in the above-ground biomass of tomato plants is uneven, in the cold season it is 25% and in the warm season up to 52% of the dry biomass falls on the generative organs. In the warm growing season, the generative organs showed the highest growth dynamics.
3) The maximum value of dry biomass increase was determined at the Mochov location in the period 2022. Experimental pepper plants at the Mochov and Suchdol locations had up to 34–39% of dry biomass accounted for by generative organs.
4) The generative organs of the tomato had the highest relative growth rate and, at the same time, the largest increase in dry biomass, while the lowest values were determined for plant stems in warm and dry periods.
5) From the previous trial of the variety Thomas F1 (Potop & Türkott 2014; Potopová et al. 2017), the ratio of fruit weight to total biomass weight is in the range of 0.58 – 0.60. Experimental Tornado F1 tomato plants at the Mochov and Suchdol sites had the maximum value of this ratio of 0.52 or 0.54.

5.4 Simulated and observed LAI development for tomato and pepper.

A comparison of the simulated LAI with the observed values of the market variety Thomas F1 grown in open field conditions at the Praha-Suchdol and Mochov locations was published for the experimental years 2014, 2015, 2016, 2017, 2018, and 2020 (Muntean et al. 2021). In this study, we present the results of market tomatoes of the Tornado F1 variety grown in field conditions for the experimental years 2020, 2021, and 2022 in Mochov and Praha-Suchdol. A comparison of the simulated LAI with the observed values of market tomato of the Tornado F1 and pepper variety Superamy F1 grown in field conditions for the experimental year 2020-2022 is shown in Figure 20-21.

A good agreement between simulated and measured LAI and model performance statistics indicates that the LAI had been calculated accurately during the CROPGRO-Tomato model calibration. At both sites, the model in 2020, exhibited the highest LAI prediction accuracy with a generally low RMSE value of 0.21 for Mochov and 0.24 for Suchdol. The simulated and observed LAI for the modelled year Mochov-2020 showed a good correlation with overestimations at 120 DAP, Lower daily mean temperature in Mochov 2020 resulted in lower observed LAI. However, at Praha-Suchdol, the model estimated a significant fit for the observed and simulated LAI in the 2020 experimental year with an insignificant overestimation at 70 DAP. In both sites, large temperature variations during the physiological growth stages reduced plant growth. The maximum LAI value was reached by Thomas F1 at the Mochov site 1.61 m^2 m^{-2} and in the Suchdol site 2.05 m^2 m^{-2}.

The maximum LAI value of 1,690 m^2 m^{-2} was reached in trials with Tornado F1 tomatoes at the Mochov location on the 235th day in 2022 and 1,571 m^2 m^{-2} at the Suchdol location. In the trial year 2021, the highest LAI values of 1.22 and 1.39 m^2 m^{-2} were reached later on the 248th day of the year at both locations.

The simulated LAI values by the model were underestimated in the range of 0.25 to 0.29 m^2 m^{-2} at both locations. However, during hot and dry weather in 2022, the highest simulated LAI values for the variety Tornado F1 were 1.96 m^2 m^{-2} at the Suchdol location and up to 1.82 m^2 m^{-2} at the Mochov location. In this growing season, however, the model underestimated LAI values in the range of 0.24 to 0.26 m^2 m^{-2} for the Suchdol and Mochov localities.

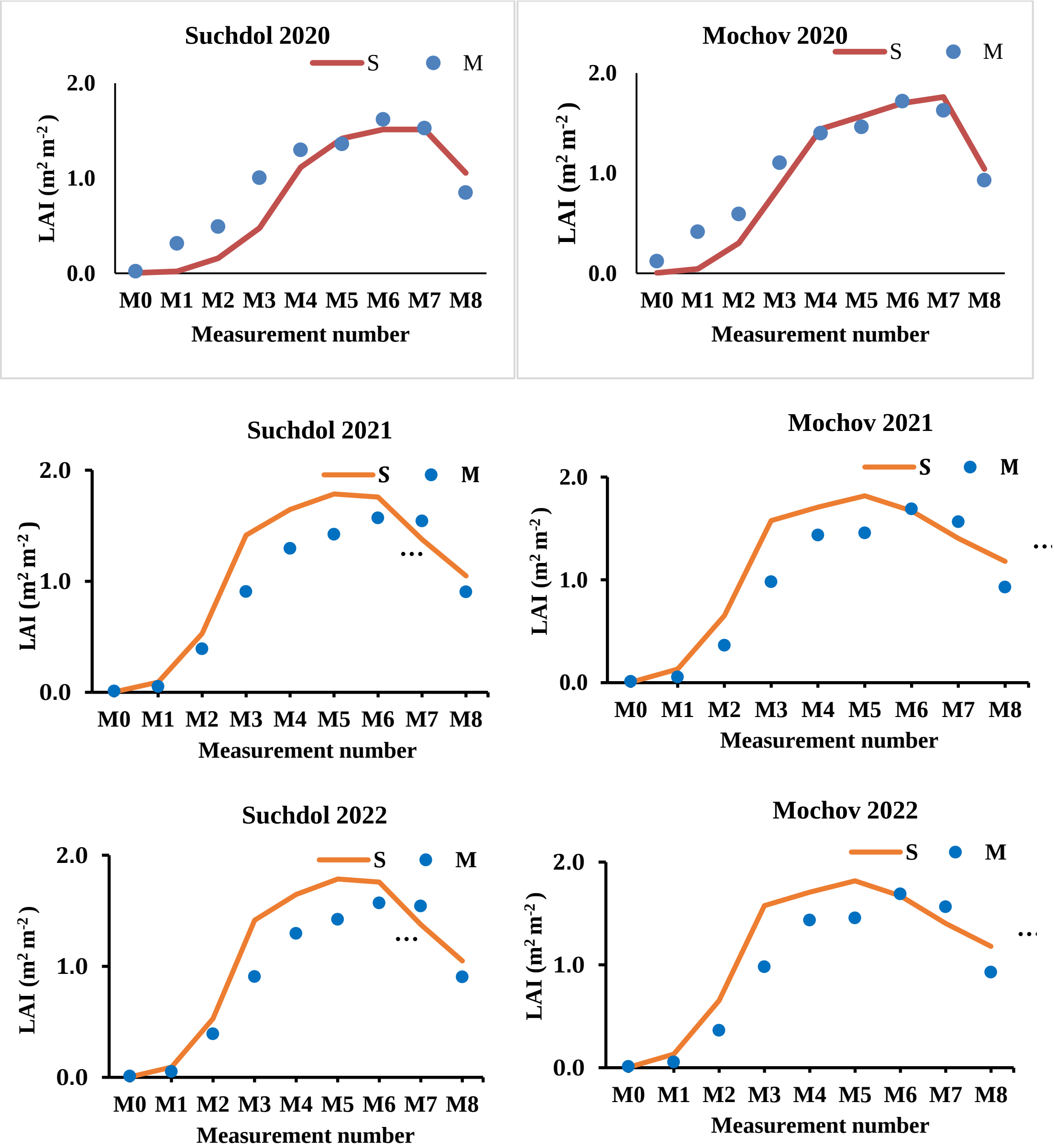

Figure 21. Graphical representation of measured and simulated values of leaf area index (LAI) in tomato variety Tornado F1 at the experimental sites Praha-Suchdol and Mochov in 2020, 2021 and 2022

The LAI_{max} of the pepper Superamy F1 was 0.910 m^2 m^{-2} at the Mochov location at the end of the 2022 growing season. In this growing season, the highest simulated LAI value was 0.86 m^2 m^{-2} and 1.27 m^2 m^{-2} on Suchdol and Mochov, respectively. The model overestimated LAI values from 0.24 to 0.26 m^2 m^{-2} for both test sites (Figure 22).

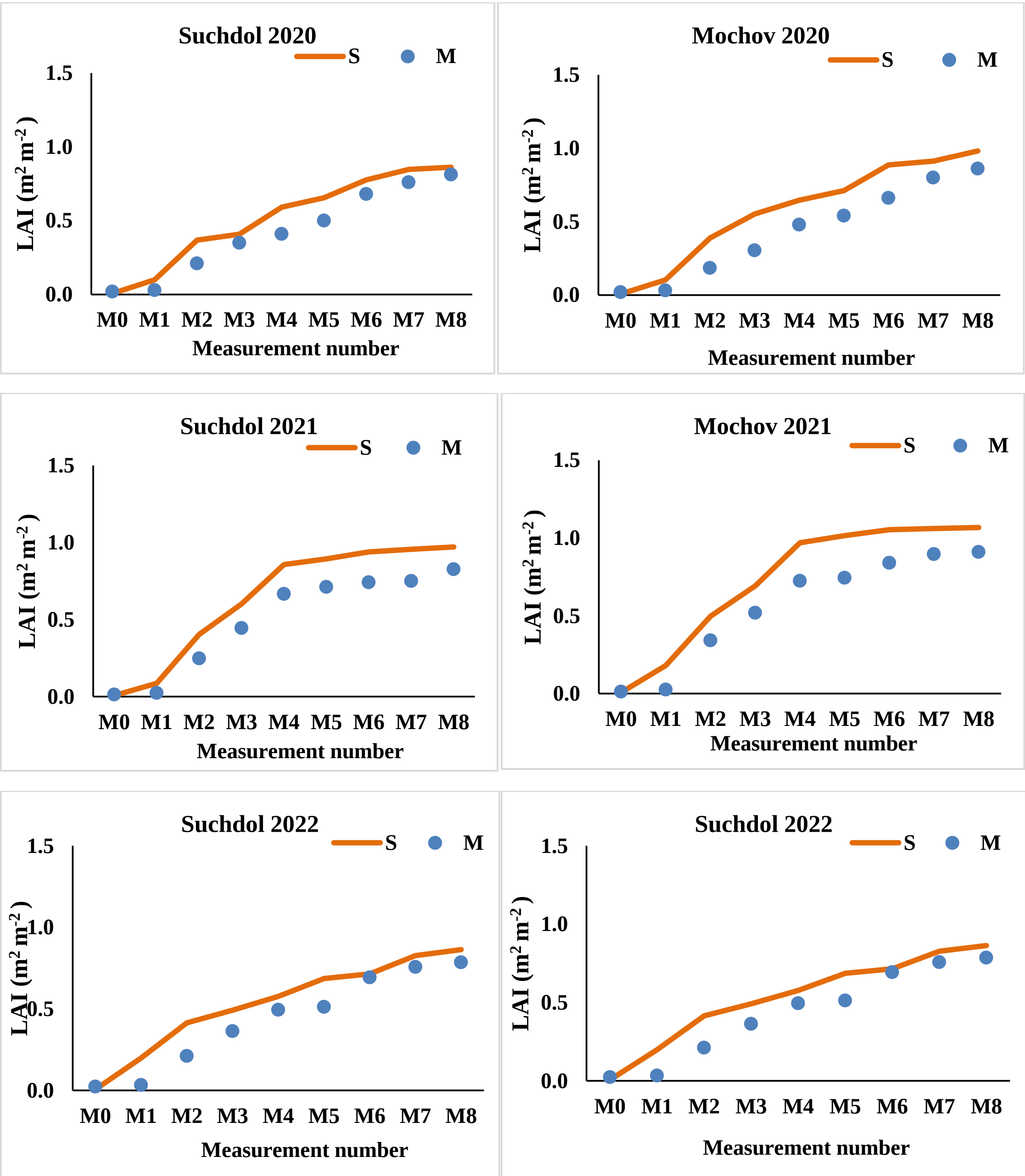

Figure 22. Graphical representation of measured and simulated values of leaf area index (LAI) for pepper variety Superamy F1 at the experimental sites Mochov and Praha-Suchdol in 2020, 2021 and 2022

Summary of experimental and model results:

- Leaf area is an important indicator that determines crop growth and production. Reducing the LAI value by removing old and some young leaves is one of the methods of yield optimization. A positive effect of LAI reduction in Thomas F1 (Muntean et al. 2021) and Tornado F1 tomato plants in Elbe lowland field conditions to increase yield by 10-15% was demonstrated.

- The amount of dry biomass is also related to the reduction of leaf area. The size of the LAI is best regulated by the density of the tomato stand. Stands with insufficiently developed leaf area and a small number of individuals (low LAI value) transmit a significant amount of unused solar radiation to the soil. The end of the growing season for tomato plants is accompanied by the fall of old, or disease-damaged leaves in the lower part of the plant. The newly formed leaf area in the apical part of the stem will not make up for these losses, and this will be reflected in the decrease of the leaf area and its dependent characteristics.
- In periods with temperature and precipitation anomalies, the model error in the LAI value was the largest at both locations. When applying the model in the conditions of the Czech Republic, the CROPGRO-Tomato model used in the simulation of LAI overestimated its value in comparison with the measured data on experimental plots, especially in periods with temperature anomalies.
- When comparing the simulation results with the field trial data, the greatest differences were noted in the combined stress periods. In such situations, the model overestimated the result compared to the field trial.

5.5 Evaluation of the performance statistics of the CROPGRO-Tomato and CROPGRO-Pepper models

In order to evaluate the performance of the CROPGRO-Tomato and CROPGRO-Pepper models during the experimental year 2022, a comparison of the simulated LAI with the observed LAI of Tornado F1 variety for tomatoes and Superamy F1 variety for peppers grown in field conditions was performed. A good agreement between the simulated and measured LAI and the model performance statistics determines the accuracy of the models in calibration. From the experimental location Prague-Suchdol, the reliability of the data with R^2 values of 0.78 and RMSE 0.37 resulted from the performance statistics during the calibration of the CROPGRO-Tomato model for the Tornado F1 variety (Figure. 23). However, for the Superamy F1 pepper variety, the CROPGRO-Pepper model during model calibration estimated a good agreement between simulated and observed LAI with satisfactory model performance statistics with R^2 (0.81) and RMSE (0.35) from the experimental site Mochov. Overall, the calibration results demonstrated the ability of the CROPGRO-Tomato and CROPGRO-Pepper models to simulate the growth characteristics of tomatoes and peppers in current and predicted climate conditions. These results can be used for the future implementation of appropriate strategies for thermophilic vegetable production systems.

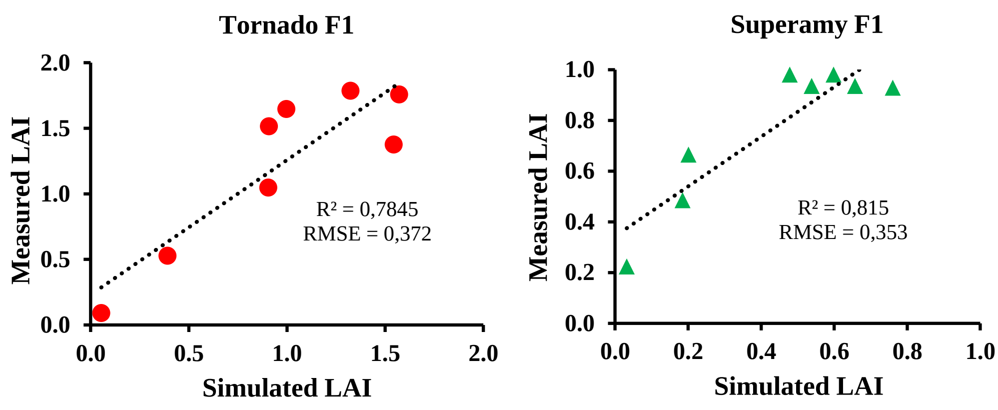

Figure 23. Evaluation of simulated leaf area index (LAI) with measured LAI values for tomato and pepper under field conditions during the experimental year 2022

5.6 Development of scenarios for simulating yield parameters of thermophilic field vegetables in the context of climate change

Yield prediction was performed using CROPGRO-Tomato and CROPGRO-Pepper (v4.8) models based on experimental crop management data, soil profile dataset, daily meteorological data from experimental sites, and the genetic coefficient for specific tomato and pepper varieties. The following temperature scenarios were generated in the DSSAT environmental module in combination with an increase in CO_2 concentration and/or decrease or increase in precipitation:

- Scenario1 – current climate (climate at the time of the field trials).
- Scenario 2 – a combination of an increase in air temperature by 1 °C and a 25% increase in total precipitation at the current CO_2 concentration (421ppm).
- Sc3 – an increase in air temperature by 2 °C and an increase of 670 ppm CO_2 compared to current conditions and with the current variability of precipitation.
- Sc4 – a combination of an increase in air temperature by 4 °C and a 50% decrease in total precipitation and an increase in the fertilization effect at the level of 936 ppm CO_2.

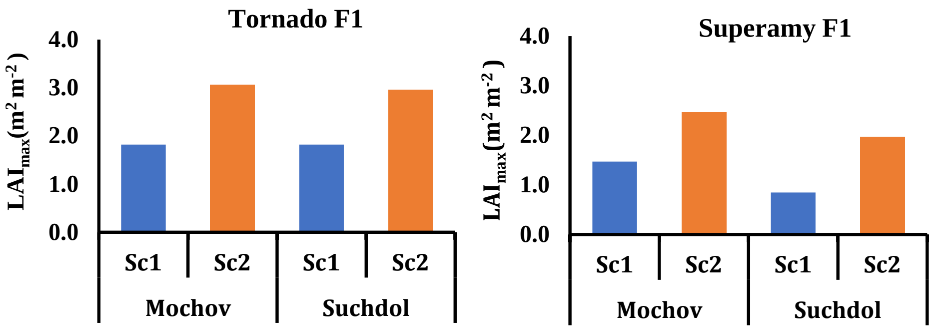

Figure 24. Simulation of the maximum leaf area index of tomato and pepper under current status (Sc1) and under a scenario with a 1 °C increase in air temperature and a 25% increase in rainfall (Sc2)

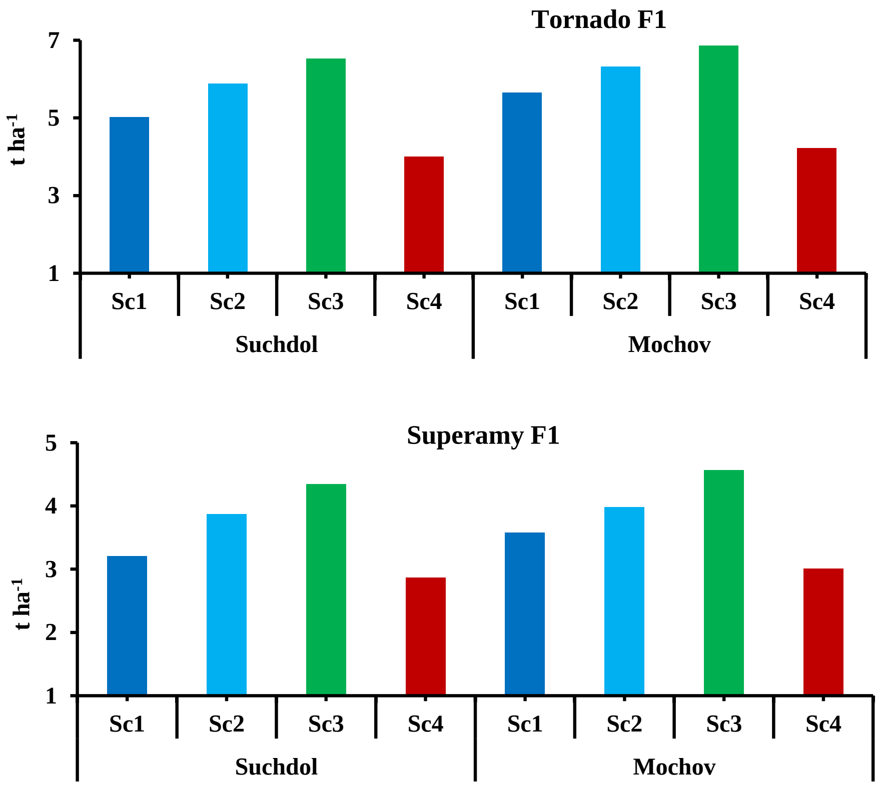

Figure 25. Simulation of tomato and pepper yields under current and future climate scenarios. The yield unit is dry matter in t ha^{-1}

Different levels of air temperature change combined with different levels of precipitation and CO_2 as an indicator of climate change can reveal regularities in the sensitivity of the simulation of crop yield parameters and/or traits of the tested varieties. Increasing the value of LAI_{max} increases the yield of Tornado F1 tomatoes, but only up to a certain limit, and it also depends on the variety, the structure of the stand and the year. The model simulated the highest LAI_{max} for both varieties according to the scenario with an increase in air temperature by 1 °C and a 25% increase in total precipitation and no changes in CO_2 concentration (Sc2). According to Sc2, LAI_{max} in Tornado F1 was in the range of 2.96 to 3.06 m^2 m^{-2} and in Superamy F1 in the range of 1.97 to 2.47 m^2 m^{-2} (Figure. 25). While the highest simulated yield in all experimental locations and varieties was obtained according to the scenario with an increase in air temperature by 2 °C and an increase of 670 ppm CO_2. For thermophilic vegetable cultivars, the simulation results pointed to the highest yield losses according to Sc4. The reason for this is the fact that the predicted occurrence of a compound events of temperature increase and a dry period tends to minimize the beneficial effect of higher concentrations of carbon dioxide. An increase in air temperature causes an increase in the amount of irrigation needed to meet the water needs of fruit and vegetables, which reduces irrigation efficiency.

Summary of the model simulation and experimental results

1) The main benefit of economic crop growth models is yield simulation. Long-term yield stability is the main prerequisite for profitable cultivation and economic profit. The simulation models CROPGRO-Tomato and CROPGRO-Pepper, which capture the physiological responses of thermophilic vegetables, provide a tool for investigating how climate change can affect the yield parameters of varieties in different agroclimatic conditions and year.

2) The median of simulated yields at the current CO_2 concentration, but an increase in air temperature by 1 °C and a 25% increase in total precipitation showed a yield of 21% compared to the median of experimental data.

3) When comparing the simulation results with the increase of CO_2 at the Sc2 scenario level with the data from the field experiment, the model overestimated the result compared to the field experiment. This means that a simultaneous increase in air temperature by 2 °C and an increase of 670 ppm CO_2 compared to current conditions and with the current variability of precipitation, the model estimates a higher productivity of tomatoes and peppers. This positive effect exceeds the negative effect of increased air temperature and rainfall variability (when applying irrigation).

5.7 Mapping the changes in the sum of effective temperatures of ripening thermophilic vegetables in the current and future climate.

This study also addresses the issue of applying different regional climate models (RCM) to estimate the temperature conditions for the full ripening of tomato varieties in the Czech Republic. Mapping results of observed and modelled changes in the sum of temperatures for thermophilic vegetables for the ensemble of RCM models under the RCP8.5 scenario for the time periods 2021-2040 and 2041-2060, respectively, with the reference period 2001-2020 in the Czech Republic are shown in Figure 26. The expected rise in temperature, which will result in an earlier reaching of the temperature sum necessary to reach technical maturity, should create sufficient temperature conditions for growing thermophilic vegetables even in the still colder regions.

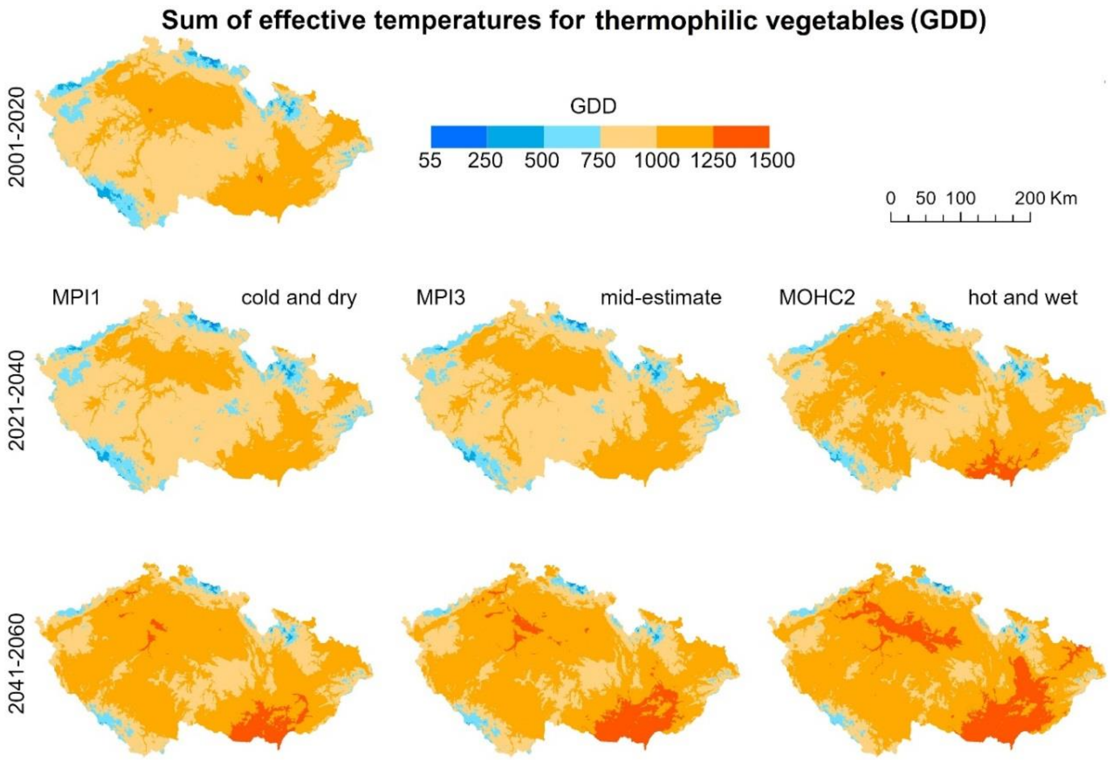

Figure 26. Observed and modelled changes in the sum of temperatures for thermophilic vegetables under the RCP8.5 scenario and for the ensemble of RCM models
(The mean estimate (MPI3), the warmest and wettest model (MOHC2) and the coolest and driest model for the time periods 2021-2040 and 2041-2060, respectively, with the reference period 2001-2020 in the Czech Republic). Source: Potopová et al. (2023)

For the observed period (2001-2020), the area with the sum of effective temperatures for growing tomatoes (GDD >1000 °C) represents about 36.60 % of the territory. In the future, according to the climate models used, for the periods 2021-2040 and 2041-2060, the area with a probability of effective temperatures above 1000 °C will increase considerably. In the case of the median estimate models, the area will practically double in the period 2041-2060 compared to the current period (2001-2020) and will represent about 72.01% of the territory. In the case of the median estimate model, for the period 2021-2040, there will be an insignificant reduction, the area will represent about 34.83% of the territory. The largest increase would be in the case of the warmest and wet model, for the period 2021-2040 it will represent 56.09%, and for the period 2041-2060, 79.85% of the territory. In the case of the coldest and drier model, for the period 2021-2040, there would be a decrease in the area, which would represent about 28.27% of the territory. In the case of this model the smallest increase would be attested for the period 2041-2060, compared to the median estimate models. Thus, the area with the sum of effective temperatures above GDD >1000 °C will represent 68.58% of the area in the period 2041-2060.

5.8 The risk of damaging spring frosts under current and future climate scenarios

Three model projections were also used for the estimated potential changes in the occurrence of late spring frosts. The spatial distribution of the end date of the last spring frost in the current and future climate for three RCMs is shown in Table 23. In the current climate, the date of the end of the last spring frost was in the period until 30 April over an area of 9 359.55 km^2 (79.55 % of the Czech Republic). In May, mild spring frosts were recorded over an area of 6,778.97 km^2, which is about 8.59 % of the territory. Spring moderate frosts in the period up to 10 April affected an area of 25 379.70 km^2 (32.16 % of the territory). In May, frosts of moderate intensity were recorded only over an area of 1 215.32 km^2 (1.54 % of the territory). The end date of the last spring intense frosts was up to 25 April, and the spring intense frosts affected an area of 57 988.21 km^2, which is about 73.48 % of the territory.

Table 18. Dates of the end of the last spring mild frost in the number of days from January 1 in the periods 2001-2020, 2021-2040 and 2041-2060 on the territory of the Czech Republic (78,917 km2) expressed in relative units (%)

	2001-2020	2021-2040			2041-2060		
Day of the year	Current status	Cold and dry model	Mid-estimate	Hot and wet model	Cold and dry model	Mid-estimate	Hot and wet model
<105	11.86	49.78	35.17	77.78	63.59	81.64	93.65
106-120	79.55	46.58	56.69	19.76	33.24	16.96	6.06
121-130	6.90	3.29	6.14	2.15	2.91	1.29	0.28
>130	1.69	0.35	2.0	0.0	0.26	0.10	0.01

In the period 2041-2060, data on the end of the last spring mild frosts indicate a significant shift in their occurrence to the first half of April in most areas. In the case of the coldest – also drier scenario, the date of the end of the last spring mild frost by the first half of April, they will occur in 63.59% of the territories, in the case of the middle estimates 81.64%, in the case of the warmest model – also wetter scenarios in 93.65% of the territory.

Summary of regional climate models:

- Based on the evaluation by the combined climate and crop model, the favourable temperature for fruit ripening of tomato areas will increase in the Czech Republic corresponding with the probability of the occurrence of GDD>1000 °C.
- From the perspective of field vegetable production, late spring frosts remain a risk factor, but the level of risk is decreasing. The earliest termination of the last spring frosts was experienced by localities with warming sandy soils along the middle course of the Elbe with a high concentration of vegetable farms.

6. SUMMARISATION AND DISCUSSION

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 (Boote K 2017). Tomato has served as a pioneering vegetable species in the field of vegetable crop modelling. In recent decades, most of the tomato modelling effort has focused on understanding carbon fluxes and development processes associated with the crop's environment (Boote et al. 2012b). The CROPGRO-Tomato model was adopted by (Scholberg et al. 1997) to simulate field-grown tomatoes. (Boote et al. 2012b) developed a module for predicting fresh tomato weight and fruit size, which was added to the DSSAT software.

In the Czech Republic, the CROPGRO-Tomato model was applied for the identification of suitable locations for the expansion of a novel collection of thermophilic vegetable varieties in the Elbe lowland region, taking into consideration the distinct climatic changes specific to the area (Potop & Türkott 2014; Potop et al. 2014a, 2014b). In recent years the application of CROPGRO-Tomato and CROPGRO-Pepper models to simulate the growth parameters of tomato were provided by Muntean (2021) and Potopova (2023). Researchers from the Czech Republic have applied climate models in their studies to understand better how the impacts of climate change on agriculture may affect the field vegetable productivity (Potopová V et al. 2014; Potopová et al. 2016, 2021; Trnka & Hlavinka 2020).

The presented work is focused on the evaluation aspects of dynamic crop simulation model, which was calibrated and validated under experimental field conditions. These performance evaluations of the CROPGRO – Tomato and CROPGRO – Pepper models can be used in a variety of ways, ranging from farmer-level crop production strategies to policy planning for the entire agricultural sector. The research is based on modelling the effect of compound weather events on the development of the growth characteristics of thermophilic vegetables. The general information about tomato variety and experimental data on phenology and yield components has been previously described before (Potopová et al. 2017). Tomatoes, peppers, and eggplant were chosen for the experiment, because in the future, due to climate change and increasing air temperature, favourable conditions are expected for the cultivation of these vegetables, under the condition that minimum irrigation is observed. During the growing season, the phenology (i.e., the phase of plant growth) of the crops was continuously monitored and it was determined in which phase the crops the most water needed. Biomass was also collected, leaf area, weight of ripe fruits and other parameters were evaluated. A chemical and hydrological analysis of the soil was also carried out. The collected data served to validate the growth models of vegetables. Although cold and wet periods alternated with hot and dry events at the experimental locations, above-average yields of the Tornado F1, Superamy F1 and Baikal F1 were recorded in it, compared to the average yield in Central Bohemia.

6.1 Performance evaluation of CSM- CROPGRO-Tomato and CROPGRO-Pepper models

At global, regional, and local levels, there is limited data on the genetic coefficients of the tomato and pepper varieties. The CROPGRO-Tomato and CROPGRO-Pepper crop models in DSSAT version 4.8 demonstrated a good ability to simulate LAI and observed yield for the crops studied. The latest version of this model is therefore a reliable tool for determining the genetic coefficients of local varieties and assessing their resistance to future climate change. The leaf area development was compared, and although the modelled values were higher than the measured values, they were still within a reasonable range. The model fitted the observed LAI data with an RMSE of 0.37 for tomato and 0.35 for pepper. The maximal simulated crop yield across all experimental sites and cultivars was achieved under the conditions of a 2°C rise in air temperature with an elevation in carbon dioxide concentration to 670 parts per million, herein referred to as Scenario 3. The calibration statistics indicate that the model has been effectively calibrated and is now prepared for the assessment of experimental variations under diverse climatic conditions.

The CSM- CROPGRO-Tomato and CROPGRO-Pepper models used in this study has successfully passed rigorous testing and have been reviewed in a reputable scientific journal, confirming its validation and suitability for application in the specific field conditions of the Czech Republic. In addition, the results of this research have been documented in a certified practical methodology officially approved by the Central Institute for Supervision and Testing in Agriculture under Reference No. UKZUZ 106522/2023 (Potopová et al. 2023a).

In a study, (Ayankojo & Morgan 2020) also observed similar ranges of FL-SH, EM-FL, and FL-SD in the cultivar file for Florida's 47 cultivars of tomato. This result was in agreement with (Scholberg et al. 1997) and (Boote et al. 2012b), who noted that tomatoes grown in the open field reached a maximum LAI at about 11 weeks after transplanting. Therefore, our experimental data show that fruit formation in tomato and pepper cultivars decreased with increasing temperature extremes and rainfall. Therefore, the largest differences between measured and simulated LAI values were recorded in the GSs with the coldest and wettest events. This is in agreement with (Khan et al. 2015), who noted that negative and non-uniform temperature variations during the tomato and pepper growing season could affect biomass accumulation. Studied crops growth at low temperatures resulted in a lower number of flowers, number of fruits and yield per hectare as compared to plants produced at optimum temperature. The same results were obtained by (Boote K 2017). Low temperature stress during vegetative growth stages significantly reduced the yield (Meena R et al. 2018). Conversely, extreme temperatures can cause heat stress, which leads to decreased fruiting and a greater distribution of resources (carbon, water and nutrients) in the vegetative biomass (Young et al. 2004; Alam et al. 2010; Ozores-Hampton et al. 2012; Heuvelink E et al. 2018) concluded that single-leaf photosynthesis and plant biomass development have an optimal temperature range of 20 and 30°C at 350–410 ppm CO_2 concentration. In another research conducted by (Ogweno et al. 2009) optimal photosynthesis of tomato leaves occurred at 25°C, while it started to decrease higher 38°C. The tolerance of studied crops to extreme temperatures and lack of precipitation, compensated by irrigation, will probably become important for farmers in Elbe Lowland. For the production of studied crops (Boote K 2017), it is necessary to: (i) ensure the water and nutritional requirements of the crops for optimal production, (ii) take into account the environmental impact of production, and (iii) provide nutritious and safe vegetables for consumers.

(Cammarano et al. 2022) also applied the CROPGRO-Tomato model to simulate field tomatoes for processing for three major global producing countries (USA, Italy, and China). Their model was calibrated for tomato genotypes in different environments using published scientific literature and was validated at the regional level using global processing tomato industry data for the period 2005-2019. Simulation results showed that tomato production for processing in the three main global production areas decreases by 2050 under a set of projected climate scenarios, with minor changes for SSP1-2.6 (+ 0.2 to - 9.9%) and more severe losses under SSP3-7.0 (+ 8.6 to - 8.6 %) and SSP5-8.5 (+ 6.5 to - 15.2%). The amount of water necessary for irrigation will increase by between 5 and 50 % depending on the region. China is expected to have lower water consumption compared to California and Italy, suggesting that China has the potential to become one of the important regions and major centres for tomato production for processing by 2050. The estimated water consumption for irrigation may put pressure on water resources in the future, which is critical in locations such as southern California and Italy. This suggests that these locations may not be able to continue their current production of tomatoes for processing. On the other hand, cold producing areas such as China and northern California could have a competitive advantage as they would be less affected by the predicted increase in temperature.

6.2 Weather risk events for growing vegetables

The amount of irrigation water applied often depends on how much water is available from local sources. The vulnerability of the production of selected thermophilic vegetables in terms of supplying their water requirements under climate change is studied by (Potopová et al. 2022). A significant increase in irrigation requirements can be expected in all vegetable-producing regions in the EU for 2031–2050. This suggests that adaptation strategies should be considered regionally for each species and each crop variety (Trnka et al. 2023). Vertical farming is a way to optimise vegetable supply chains and holds significant potential. Indeed, when compared to traditional technology, cultivation technologies using multi-layer stacking can reduce water used for growing lettuce by 96%. However, vertical farming systems are energy intensive, since light, temperature, and humidity need to be controlled (de Carbonnel et al. 2022), which will have a major influence on the technology uptake.

Climate change also affects the product quality of field-grown vegetables and may alter their nutritional quality. Heat stress causes decreases in the lycopene concentrations in tomatoes (antioxidants with anticancer properties) (Potopová et al. 2016). Fungal diseases (potato blight, brown spot, and leaf spot) cause a loss of tomato quality and hence reduce the yield worldwide (Panthee & Chen 2010) Because prevailing weather conditions determine the severity of the disease, crop loss may range from a mild loss of productivity to a complete loss of a particular crop resulting in great economic losses for the food industry.(Litskas et al. 2019b) examined the impact of climate change on tomatoes and their well-known pest for 29 countries in Europe, South Asia and Africa. They projected that 30-100% of the tomato-producing area under irrigation will become unsuitable for tomato production, also due to the increasing probability of mite outbreaks.

Vegetable grafting systems, aeroponics, and hydroponics are potential adaptation tools to the adverse effects of climate change. In Europe, grafted field vegetables are increasingly used in commercial production. Grafted tomatoes and other grafted vegetables tend to produce higher yields of high-quality fruit, making field cultivation financially worthwhile. In Spain, ~50 to 70 million grafts is used annually, accounting for approximately 40% of the country's tomato production (Grieneisen et al. 2018). The main advantage of modern hydroponic systems is water saving and increased productivity per area unit.

The outcomes and information generated through our analyses have crucial significance for assessing CE effects and can be consulted to predict tomato and pepper fruit formation in field conditions. We demonstrated that CEs are adverse factors that usually occur irregularly during the studied crops growing season and depend on air temperature fluctuations and precipitation received. Except for 2021, the majority of experimental growing seasons appear to be associated with positive high summer temperature anomalies and deficits in the water balance throughout the experimental sites. However, Tornado F1 and Superamy F1 cultivars generate high economic returns per unit of land and thus offers promising income prospects, especially for small landholders. The use of cultivars with spring frost and rain deficit tolerance is assumed to be an important adaptation measure for thermophilic vegetables in the Elbe lowland (Potopová et al. 2023a).

The calibration and evaluation of the CROPGRO- Tomato and CROPGRO-Pepper models in this study showed the ability of the model to simulate ongoing field management and climatic impacts on the growth characteristics of tomato and pepper.

In the study of (Holtanova et al.,) the analysis of uncertainties of the climate model outputs for the Czech Republic was applied to eight regional climate models.

They used two methods. The outcomes from both methods have indicated that the proportional impact of the regional climate model on the uncertainty associated with the simulated fluctuations in mean seasonal air temperature and precipitation alterations is most significant during the summer months and least significant during the winter months. Even if some important climate features such as temperatures and rainfall are well represented by regional models, and together with the crop growth model are crucial for studied crops development. These results can be used for future implementation of proper strategies for crop management and climatic projections.

6.3 Economic aspects

The economic evaluation of the thesis has shown the possibility of obtaining information on the impacts of management practices and the effects of climate change on the yield characteristics of thermophilic plants. Selecting the best potential varieties and predicting their yields based on dynamic crop modelling prior to experimental trials can be cost and time efficient.

Increasing the efficiency of growing and selecting suitable vegetables in specific regions will result in increasing production and reduction of losses will be reflected in the economies of vegetable production. The development of vegetable production is influenced not only by socio-economic factors, which proved crucial during the epidemic, such as restrictions on foreign trade and worker mobility but also by the effects of climate change, which can be negative (water availability, appearance of extreme weather events) and positive (possible extension of regionalisation). To increase self-sufficiency in vegetable production, it is necessary to increase the cultivated area to about twice and to reconstruct irrigation systems. Imports represent around 60 % of the total vegetable consumption in the Czech Republic, so it is necessary to increase the economic competitiveness of Czech farmers.

7. CONCLUSION

The dissertation thesis presents an analysis of the impact of predicted climate development on the production of fruiting vegetables using climate and growth models including experimental work as tools for predicting the development of the production process of thermophilic vegetables. The results can be applied in practice by gardeners and farmers from Czechia. The implementation of the obtained results will increase the quality of know-how of applied research in the vegetable industry, thus increasing the synergy between farmers and researchers. The validation of the CROPGRO model indicated that the model has been successfully calibrated and is now ready to evaluate experimental changes in different climatic conditions.

In conclusion, the calibration and evaluation of the CROPGRO-Tomato model in this study demonstrated the ability of the model to simulate the effect of ongoing field management and climatic influences on the growth characteristics of tomatoes and pepper. These results can be used for future implementation of appropriate crop management strategies. Yields of studied crops, such as Tornado F1, Superamy F1, and Baikal F1, have high economic yields per unit of land and thus offer promising income prospects, especially for small farmers. The use of varieties with tolerance to spring frost and rainfall deficit is an important adaptation measure for thermophilic vegetables grown in the open field.

The study confirmed the first **hypothesis** that heat waves and droughts will indeed intensify in the coming years. But if cultivation technologies will be respected, including drip irrigation, this risk will be reduced. During the experimental years, have not been occurred late spring frosts. From the perspective of field vegetable production, late spring frosts remain a risk factor, but the level of risk is decreasing. The earliest termination of the last spring frosts was experienced by localities with warming sandy soils along the middle course of the Elbe with a high concentration of vegetable farms.

The second **hypothesis** from the thesis is confirmed because, in conditions of climate change, the rising temperatures will result in the earlier timing of planting and stand establishment under optimal climatic conditions which is one of the main factors for achieving better crop yields, which are key components for growers to achieve better economic returns.

A third **hypothesis** also is confirmed because crop models and regional climate models was demonstrated that the expected temperature would rise, and earlier will be reached sums of temperatures necessary to achieve technical maturity of thermophilic crops. The rising temperature creates sufficient conditions for growing thermophilic vegetables outside of the current borders even in the colder areas.

At the moment, there is limited data on the genetic coefficients of the local tomato and pepper varieties. The CROPGRO-Tomato and CROPGRO-Pepper crop models in DSSAT version 4.8 demonstrated a good ability to simulate LAI and observed yield for the crops studied. The data obtained from this research represent a significant interest because will be used by DSSAT developers to improve the existing dataset for the upcoming DSSAT version 4.9.

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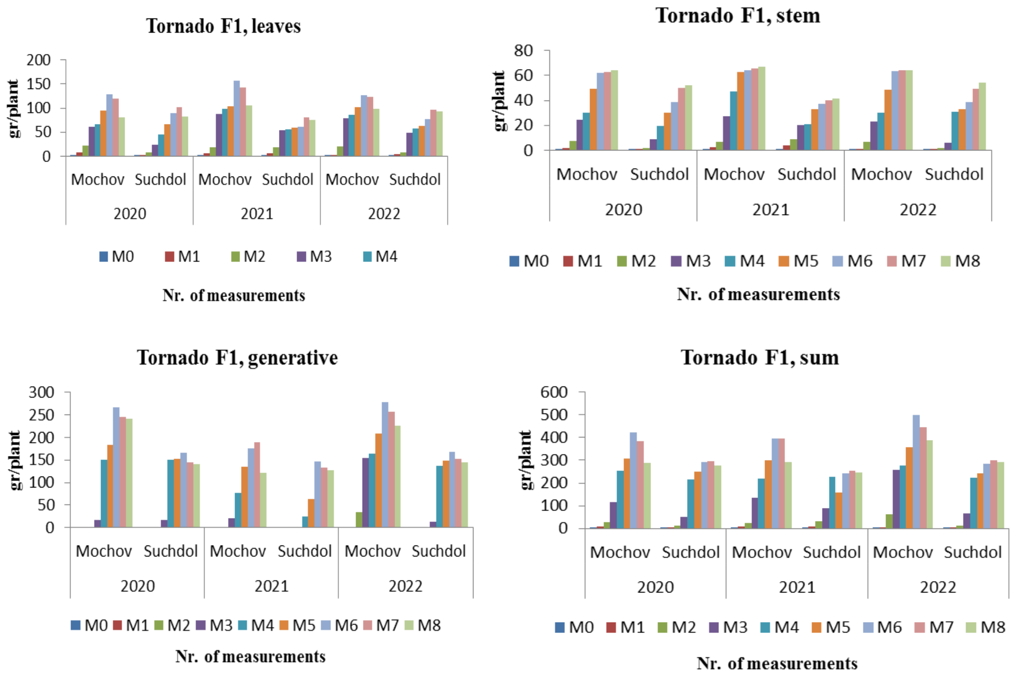
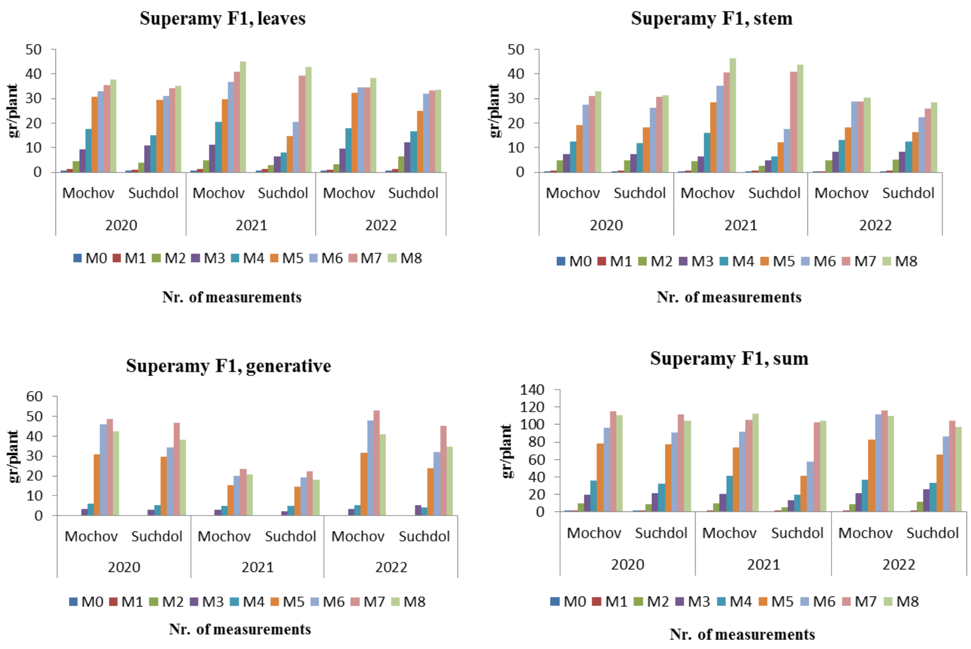
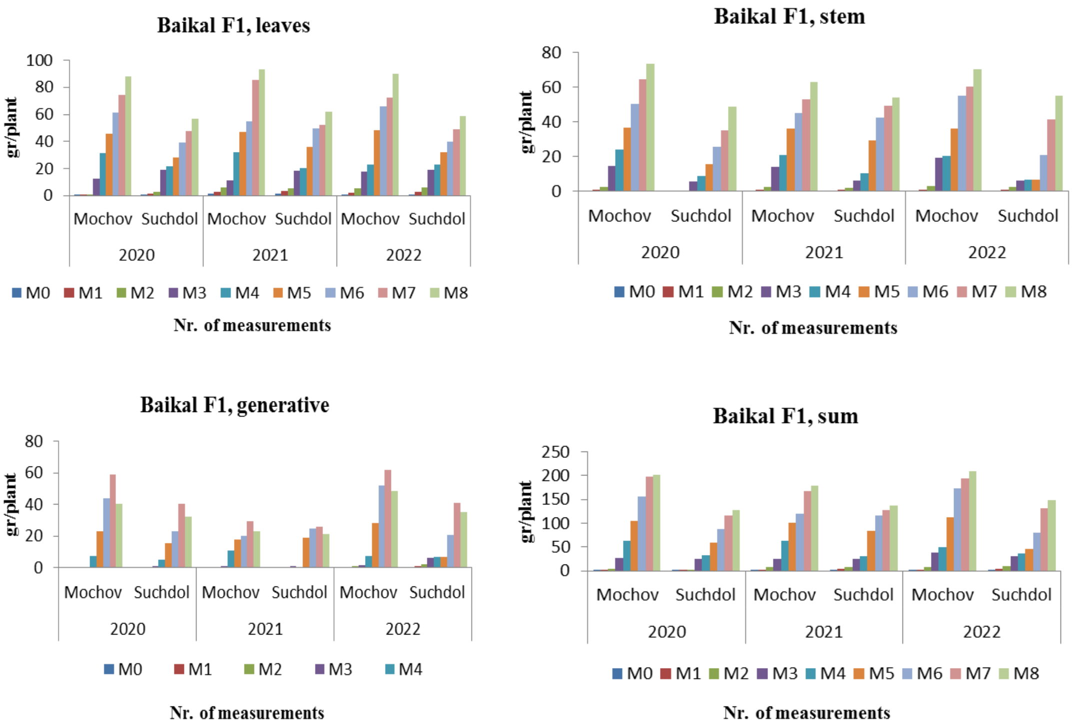
9. ANNEX



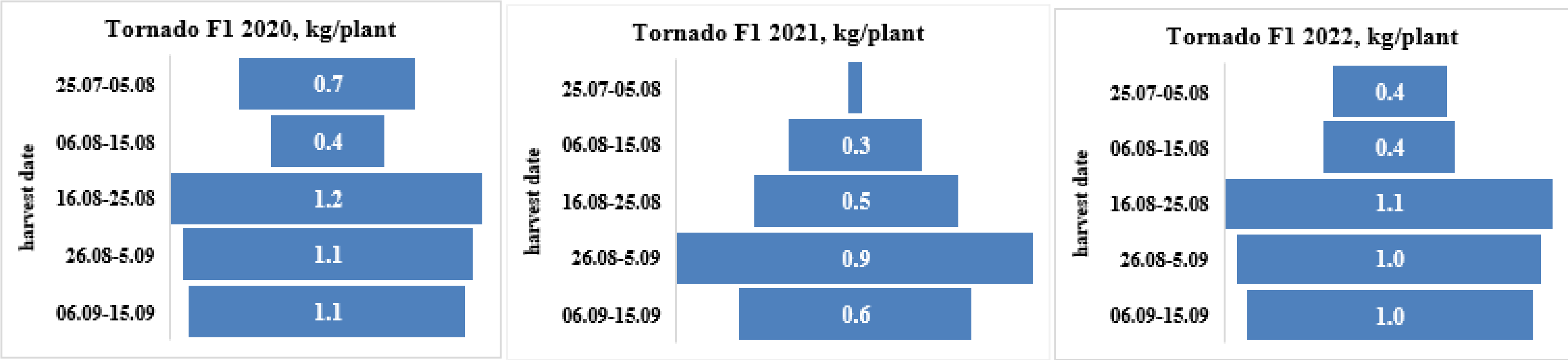
Annex 1. Determined dry biomass of individual organs for the variety Tornado F1, for two experimental sites (Mochov and Prague - Suchdol) (0- May, 1-2 June, 3-4 July, 5-6 August, 7-8 September).



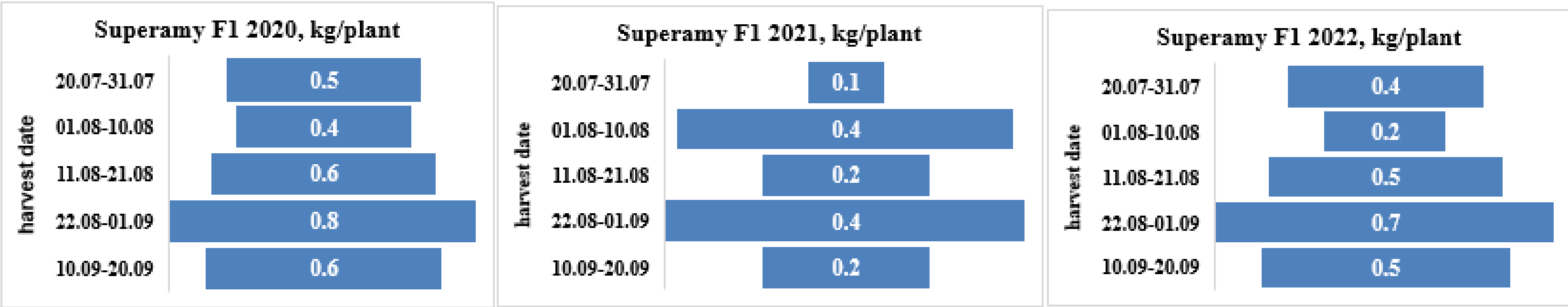
Annex 2. Determined dry biomass of individual organs for the variety Superamy F1, for two experimental sites (Mochov and Prague - Suchdol) (0- May, 1-2 June, 3-4 July, 5-6 August, 7-8 September).



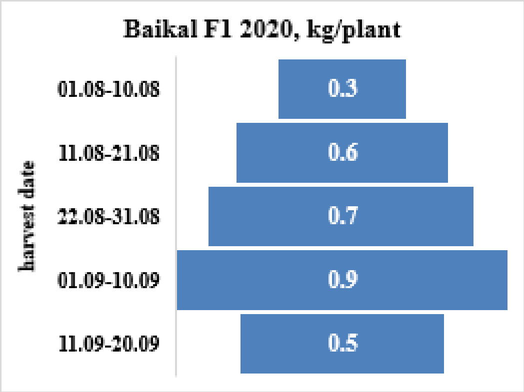
Annex 3. Determined dry biomass of individual organs for the variety Baikal F1, for two experimental sites (Mochov and Prague - Suchdol) (0- May, 1-2 June, 3-4 July, 5-6 August, 7-8 September).

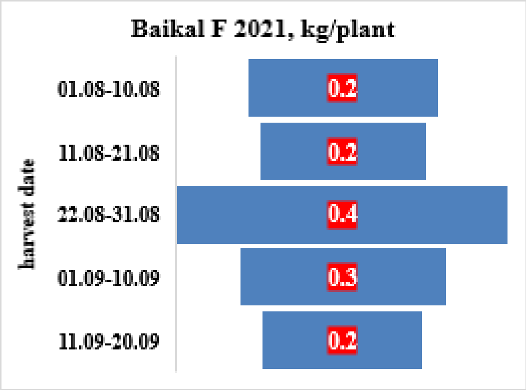


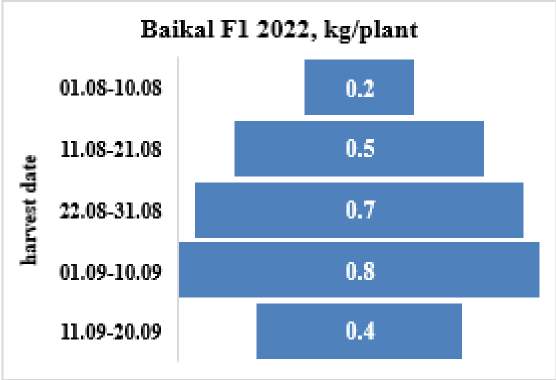
Annex 4. Time periods and quantity obtained per plant for Tornado F1



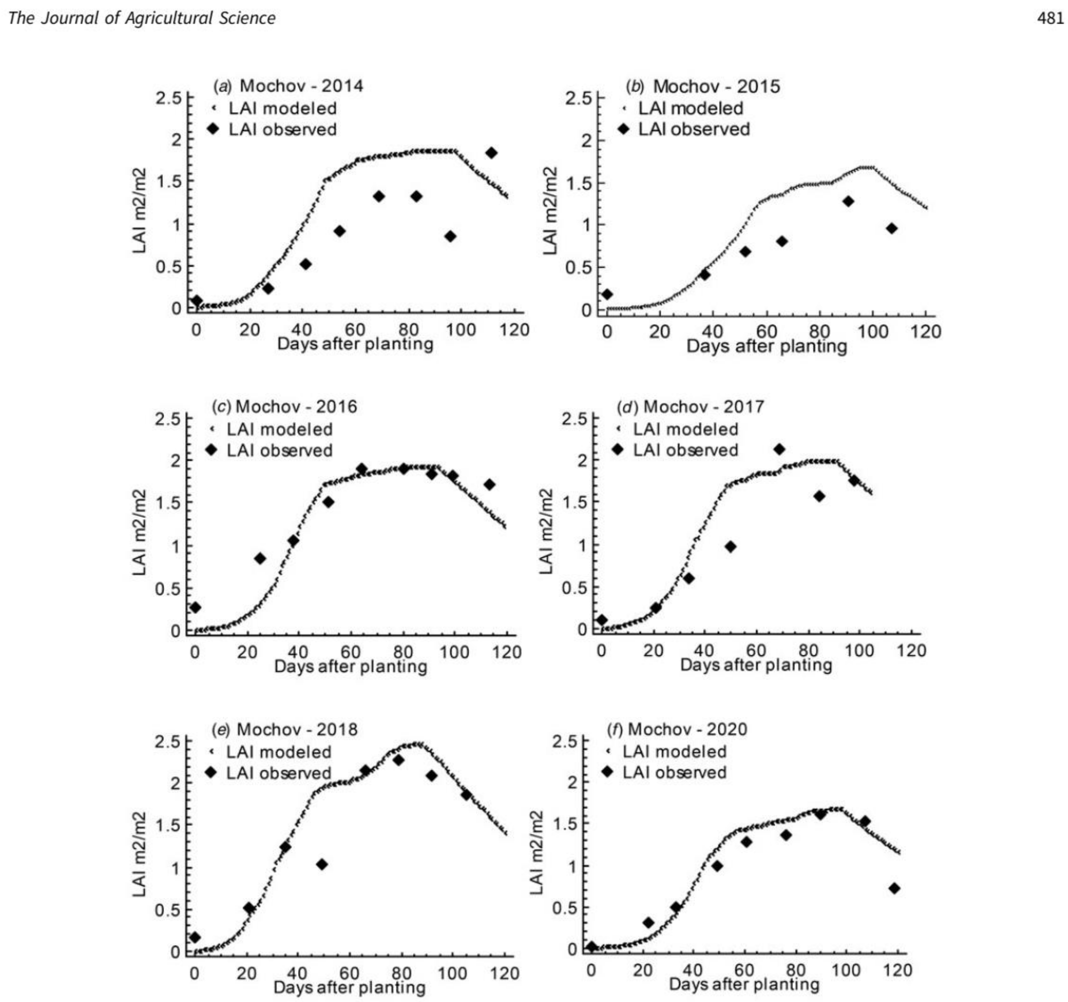
Annex 5. Time periods and quantity obtained per plant for Superamy F1



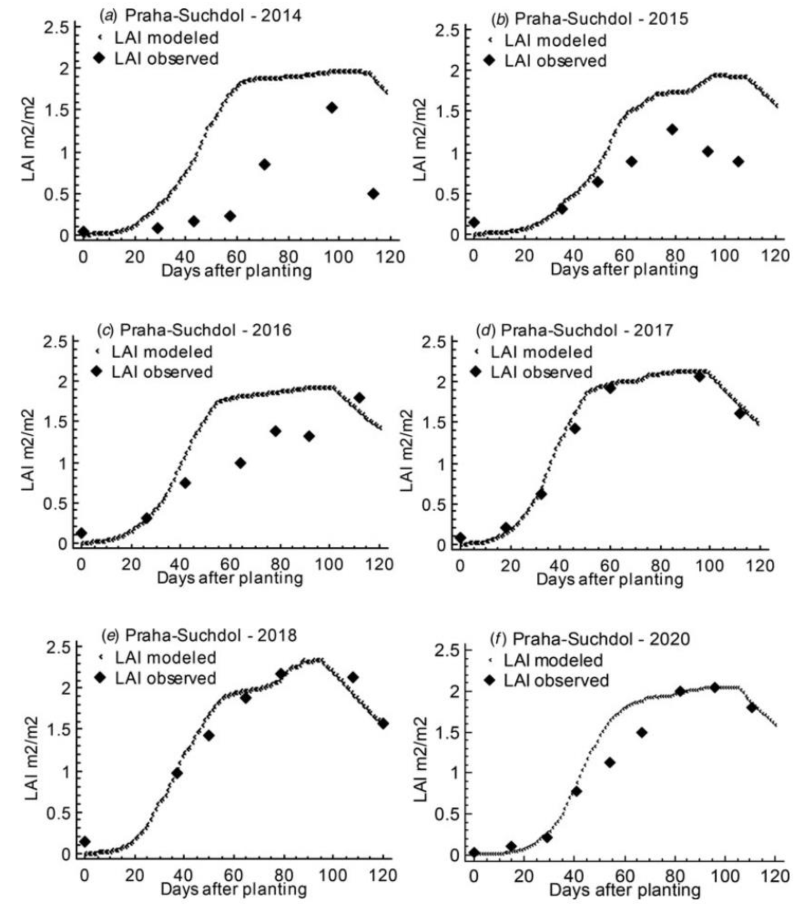




Annex 6. Time periods and quantity obtained per plant for Baikal F1



Annex 7. Comparison of the simulated Leaf Area Index (LAI) with the observed values of the fresh-market Thomas F1 indeterminate tomato cultivar grown under open field conditions for experimental years 2014 (a), 2015 (b), 2016 (c), 2017 (d), 2018 (e) and 2020 (f) at Mochov site.



Annex 8. Comparison of the simulated Leaf Area Index (LAI) with the observed values of the fresh-market Thomas F1 indeterminate tomato cultivar grown under open field conditions for experimental years 2014 (a), 2015 (b), 2016 (c), 2017 (d), 2018 (e) and 2020 (f) at Praha-Suchdol site.

Annex 9. The seedlings of the Superamy F1 variety

Annex 10. The seedlings of the Tornado F1 variety

Annex 11. The seedlings grown in the greenhouse, prepared for transplanting in the open field

Annex 12. Experimental field

Annex 8. List of Author's publications

The Journal of Agricultural Science

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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

agriculture

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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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Copulas modelling of maize yield losses – drought compound events using the multiple remote sensing indices over the Danube River Basin

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A R T I C L E I N F O

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Evaporative Stress Index
Enhanced Vegetation Index
Relative Soil Water Availability
Peak correlation timing
Coupling drought–maize yield losses mechanism
Four-variate C-vine copula
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A B S T R A C T

Danube countries have witnessed numerous waves of drought events, causing significant agro-economic loss, but three consecutive dry years amplified the debate on how to deal with future drought risk. The European drought of 2022 has shown how important it is to look at food security from an environmental droughts risk assessment approach. The coupling drought–yield losses framework derives from the understanding that all land systems are connected through coupled human and natural systems, and these social, ecological, and agro-economic impacts are the result. Maize is considered a commodity and a staple food in Europe with the largest market share in global maize exports. Drought–heat stress, war and subsequent limitations on Ukrainian trade have created a shortage of maize supply in 2022 over Europe. This study focused on eighteen countries where maize production becomes highly susceptible to drought in the Danube River Basin (DRB; Austria, Bosnia and Herzegovina, Bulgaria, Croatia, the Czech Republic, Hungary, Montenegro, Romania, Serbia, Slovakia, and Slovenia). To understand the coupling drought–yield losses mechanism, time series of maize yield datasets and multiple remote sensing indices were used on arable lands for 278 districts at a high spatial resolution. The main objective of this study was to determine which regions respond to the changes in the rate of evapotranspiration and soil moisture and in which period and how much maize production is affected. The time series of the two-band enhanced vegetation index (EVI2), the evaporative stress index (ESI), and the relative water availability (AWR) were calculated. The spatial evolution of the ESI for 4-week and 12-week time windows, EVI2, and relative soil saturation at the topsoil and rootzone layers demonstrate the progress of agricultural drought under varying agroclimatic conditions and its impacts on maize yields. Our study adopted a novel mechanism-based risk assessment approach using a four-variate C-vine copula in the perspective of modelling yield losses. To assess how much maize production can be limited by drought stress, the weekly dynamics of the strength of bivariate linkage of eight compound modes were provided. The return periods of drought–yield losses signatures in the study region were less than 4 years. The highest chances (once every 2.50–2.86 years) of the occurrence of drought–yield losses signature occurred in Romania, Bulgaria, Slovakia, Bosnia and Herzegovina. The availability of soil water is one of the crucial indicators (AWR40) that explain the high degree of yield variability. This is an alarming finding given the expected or increasing year-to-year variability in soil moisture in these regions. The joint cumulative distribution function ($F_{CROP,\ ESI,\ AWR40,\ AWR100}$) suggests that shorter-term ESI will be most beneficial for maize yield estimation in agricultural districts where crop productivity is primarily impaired by warmer and drier events. This combination of effects can cause short-term compound hot and dry extremes characterized by rapid onset, severe intensity, and devastating impacts on crop production. Droughts between 2015 and 2022 challenged governments across the Danube basin and highlighted the need for intergovernmental interactions and coordination. For the DRB area, user-oriented drought monitoring portals are already providing

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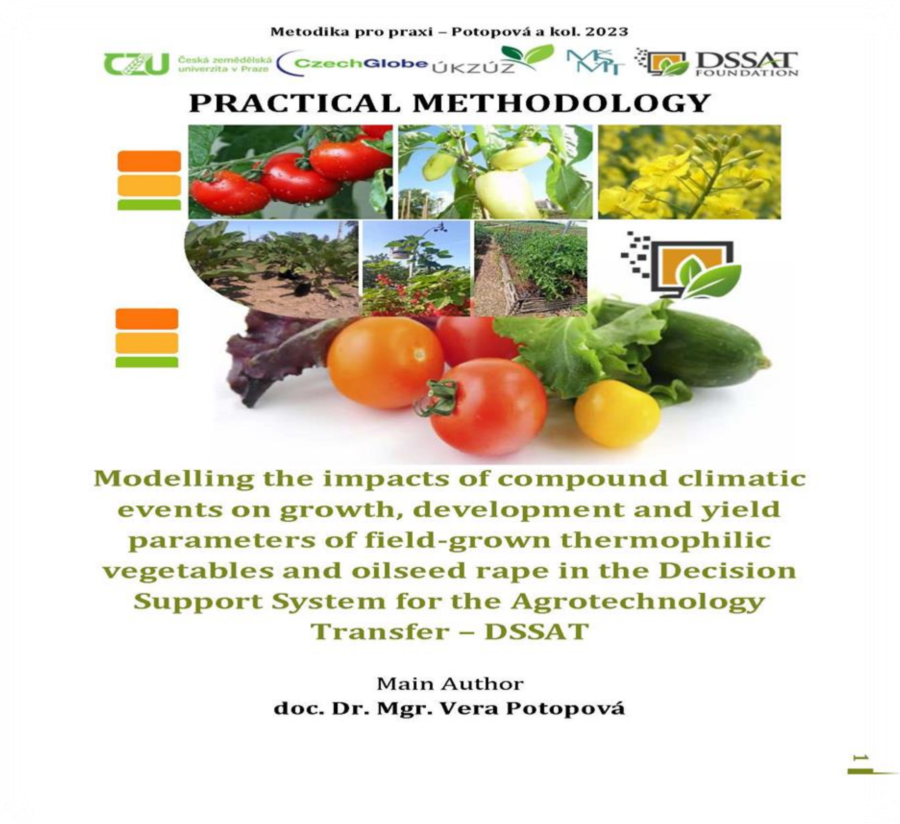

Metodika pro praxi – Potopová a kol. 2023

PRACTICAL METHODOLOGY

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
doc. Dr. Mgr. Vera Potopová

1

Metodika pro praxi – Potopová a kol. 2023

2023

ČESKÁ ZEMĚDĚLSKÁ UNIVERZITA V PRAZE

FAKULTA AGROBIOLOGIE, POTRAVINOVÝCH A PŘÍRODNÍCH ZDROJŮ

Katedra agroekologie a rostlinné produkce

Ústřední kontrolní a zkušební Ústav zemědělský

Ústav výzkumu globální změny AV ČR v.v.i

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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Ing. Igor Potop
Mgr. Pavel Zahradníček, Ph.D.
Dr. Ing. Martin Možný

Metodika simulace produkce plodin, hospodaření s vodou a živinami, klimatických rizik a environmentální udržitelnosti v DSSAT

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Česká zemědělská univerzita v Praze

Zemědělské a biologické inženýrství
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CROPGRO-Tomato MODEL FOR SIMULATING IMPACT OF COMPOUND CLIMATE EVENTS ON TOMATO GROWN

iCROPM 2020 | Crop Modelling for the Future | Crop Modelling for Agriculture and Food Security under Global Change | February 3-5, 2020 | Le Corum Conference Center, Montpellier, France

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1. Introduction

Compound climate events (CEs) have a huge impact on yield, speed of ripening and the presence of vitamins in the grown product (Fig. 1). Modelling the interactions between a number of competing events is much more complex than modelling the drivers of individual events. Dynamic crop simulation models can be useful tool to simulate the wide-ranging effects of CEs on vegetables 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., 2010). Tomato has been a pioneer vegetable species for crop modelling. Theoretical and experimental researches on the use of CROPGRO to predict vegetables growth using the example of tomato (*Solanum lycopersicum* L.) have been carried out.

2. Materials and Methods

This paper focuses on the modelling the impact of CEs on the growth, development and yield of the hybrid field tomato variety LSL Thomas F1 on the locality Prague Suchdol using the BBCH phenological phases and growth analytical characteristics during the period 2014 - 2018. We subsequently, computed joint return periods to estimate the risk (occurrence probability) of four compound extreme modes: T35/P35, T35/P85, T85/P35 and T85/P85, indicating combinations of extreme cool-dry, cool-wet, hot-dry and hot-wet events during the GS, respectively.

2.1 Description of case study area

- The study was conducted at 2 sites in the middle Elbe lowland (valleys of the Elbe River basin; i.e., the central parts of the Czech Republic). This fruiting-vegetable-producing region is characterized by the warmest and driest climatic conditions, where drought stress is often a limiting factor for crops.
- The agro-climate conditions of the fruiting region ensure the longest growing season and the longest frost-free period with the most productive soil conditions. The planting dates for fresh-market tomato bush cultivars grown under open field conditions correspond to the stable transition of the average daily air temperature through 15°C (season lengths more than 110 days).
- During 1961-2014 (1989-2014), the mean temperature of the tomato growing season ranged between 16.5°C (17.1°C), and the total precipitation varied from 289 mm (291 mm) to 325 mm (319 mm). The average maximum and minimum temperatures were 22.1°C (22.7°C) and 11.3°C (11.8°C), respectively .

2.2 Model input data set

2.2.1Description of CROPGRO –Tomato model

- To run CROPGRO model, we used the following 4 basic dataset groups: (1) crop species and cultivar characteristics; (2) meteorological daily data: rainfall (mm), solar radiation ($MJm^{-2}d^{-1}$), maximum and minimum air temperatures (°C); (3) soil conditions and (4) cultivation technology (term of transplanting, term and dose of irrigation, fertilizing, harvesting) (Tab. 1-6; Fig. 1-4).
- Field datasets were used for the CROPGRO-Tomato model evaluation (Tab. 1), which is part of the DSSAT V4.5 software (Hoogenboom et al., 2010). We applied the newly calibrated values of genetic crop and cultivar coefficients (Tab. 3-5) for version 4.5 of CROPGRO-Tomato model (Boote et al., 2012).

2.2.1 Weather data

- The study has connected daily weather data recorded at Poděbrady and Praha-Ruzyně climatological stations (1961-2018) from the CHMI and daily weather variables recorded by meteorological sensors in crop canopy at field and farm levels (Hanka Mochov s.r.o., 189 m a.s.l. and Praha-Suchdol, 287m a.s.l for the period 2014-2018).

2.2.2 Crop data

- General cultivar information and experimental data on phenology and yield components are presented in Tab. 2a-b. The measured and simulated growth and development of the fresh-market Thomas F1 tomatoes bush cultivars grown under open field conditions in two different sol-climate locations in the Elbe lowland were evaluated. The treatments selected for evaluation were well-irrigated and well-fertilised, and therefore, no water or N stress was evaluated. The sampling plants were collected a once 14 days for analysis of basic physiological parameters: LAI (Leaf area index), LAR (Leaf Area Ratio), C (Crop Growth Rate), RGRw (Relative Growth Rate) and NAR (Net Assimilation Rate).
- Phenology observation was done weakly. This model simulates development based on multiple phases from planting o harvest (Fig. 3). Parameters affecting leaf growth, dry biomass productions, and dry biomass of leaves, stem and generative organs from planting to harvest were calibrated against the measured data.

2.2.3 Soil data

- Haplic Chernozems (Praha-Suchdol, 1st site) and sandy-loamy Cambisol (Mochov, 2nd site) are the prevailing soil groups.
- Specific soil parameters required for model input such as lower limit (LL), drained upper limit (DUL) and saturation, drainage coefficient and runoff curve number were estimated from measured soil profile data (Tab. 2c) using the **Sbuild program** available in DSSAT.

2.2.4 Model calibration and evaluation

- The main objective of model calibration was to adapt the model parameters to local environmental conditions (e.g. soil types and weather conditions) and crop cultivars (Tab. 2c-d and Fig. 4) to gain a good overall agreement between simulated and observed values. CROPGRO model was calibrated using the experimental data presented in Tab. 2a-b and Fig. 4.
- Statistical indicators, i.e. RMSE, index of agreement (d) and coefficient of determination (R) were used for evaluating the performance of CROPGRO-Tomato model.

The global tomato processing

Fig. 1 The current largest producers of tomato

Farm trial tomato fields, Hanka Mochov s.r.o – regional producer of vegetables

Fig. 2 Location of fields for tomato cultivars at two experimental sites: A) Thomas F1– Mochov farm, B) Thomas F1 – Praha Suchdol.

Trial tomato fields of CULS, Praha-Suchdol

Propagation of local vegetable farmers

3. Results

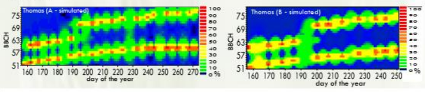

Fig. 3 Observed and simulated evolution of phenological stages and percentage of plants occurring from 51 to 79 BBCH for tomato cultivars at two experimental sites: A) Praha Suchdol, B) Mochov farm

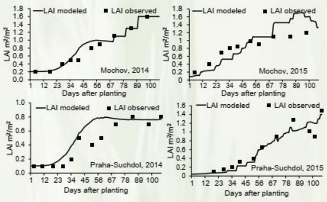

Fig. 4. The comparison of the simulated LAI with measured values (2014-2015).

- The weather conditions during the growing seasons of 2014 and 2015 produced an extreme drought and heat stress.
- Moreover, the developmental stage of a vegetative unit at which the leaves are removed influenced LAI strongly and therefore crop growth rate.
- Early leaf pruning decreased LAI as well as biomass.

Tab 6. Analysis of RGR, LAI and CEs (hot days [HD], heat stress index [TS30], dry days [DD], dry-hot/hot-wet days [DH/HW]) from transplanting to harvest of Thomas

years	RGR, $g\,g^{-1}\,day^{-1}$	LAI_{max}, $m^2\,m^{-2}$	LAI_{max}, day	Yield, $t\,ha^{-1}$	HD/DD, days	TS30, °C	DH/HW days
2014	1.94	0.5075	254.	22.2	13/67	28.4	5/2
2015	3.51	1.4831	257.	49.0	30/85	115.8	22/4
2016	4.71	1.7846	251.	41.7	13/70	20.3	12/1
2017	5.00	2.5393	221.	69.8	14/79	12.8	3/1
2018	4.26	4.1334	241.	72.1	33/96	77.1	20/1

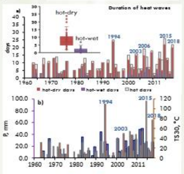

Fig. 5. The frequency of hot days, hot-dry and hot-wet days in the heat waves.

Tab. 1 Modeling approaches of CROPGRO-Tomato (DSSAT) for major processes of crop growth and development.

	Processes	CROPGRO-Tomato model
1.	Crop phenology	Function of temperature, photoperiod
2.	Leaf area development and light interception	Simple: leaf area expansion is driven by temperature as a function of leaf number and assimilate availability
3.	Light utilization	Descriptive radiation use efficiency approach. Constant radiation use efficiency is used to directly convert absorbed radiation into dry matter
4.	Dry matter accumulation	Driven by temperature as a function of phenology, limited by assimilate availability, excess assimilate partitioned to roots
5.	Rooting distribution over depth	Exponential
6.	Method to calculate evapotranspiration	Priestley–Taylor
7.	Water dynamics	Capacity approach, multi-soil layer
8.	Model type	Crop specific, dynamic
9.	Simulation time step	Daily

Tab. 2b Experimental measurements

Site	Year	Cultivar	Planting date	Days from planting to beginning maturity	Yield (t/ha)
Mochov	2014	Thomas F1	21 May	33	25.2
	2015	Thomas F1/ Pálava F1	12 May/12 May	55/51	13.2/13.7
Praha-Suchdol	2014	Thomas F1	21 May	37	22.2
	2015	Thomas F1/ Pálava F1	11 May/11 May	63/58	24.5/30.0

Tab. 3 Modified parameters in ecotype file, calibrated values by Boot et al. (2012)

Parameter	Calibrated values
Time between planting and emergence PL-EM (Td)	6
Time between emergence and first true leaf EM-V1 (Td)	22
Time required for growth of individual fruit LNGSH (Td)	39
Time between first flower and last leaf in main stem FL-VS (Td)	45
PMO6, if PM06 is 0.0, there is no slow growth phase; if PMO6 greater than 0.0, there is a slow growth phase	0.55
Rate of leaf appearance on main stem, TRIFL	0.45

Td – thermal days

Tab. 4 Modified cardinal temperature for the CROPGRO-Tomato model in species file (Boote et al. 2012)

Physiological process /BBCH stages	Cardinal temperature values [°C] T_b	T_{opt1}	T_{opt2}	T_{max}
Rate of leaf (or truss) appearance (vegetative development)/ 10-29	7.0	22.0	28.0	48.0
Rate of progress to anthesis/truss appearance rate (early reproductive development)/51-69	7.0	22.0	28.0	48.0
Rate of fruit development and maturation (late reproductive development)/71-89	5.2	26.0	28.0	48.0
Relative effect of temperature on fruit addition and pollination	6.0	21.0	26.0	33.0
Relative effect of temperature on individual fruit	6.0	22.0	25.0	32.0
Rate of light-saturated leaf photosynthesis	6.0	28.0	34.0	48.0

Tab. 2a General long-term climate (1981-2010) and agronomic information during growing season of field-grown tomatoes bush cultivars in experimental sites.

General information of cultivars Thomas F1/Pálava F1	Experimental sites Mochov	Praha-Suchdol
Altitude (m.a.s.l.)	189	287
Rainfall (mm)	345	318
Water consuming (mm)	450	450
Requirements for irrigation (mm)	High	High
Mean temperature (°C)	16.5	16.1
Maximum temperature (°C)	22.9	21.4
Minimum temperature (°C)	11.3	10.5
Global solar radiation ($MJ\,m^{-2}\,d^{-1}$)	2553.7	2439.2
Days from planting to flowering (days)	27/17	25/24
Days from planting to beginning maturity(first harvest (days)	44/51	50/58
Days from planting to last harvest (days)	120/121	138/154
Plant height (cm)	2000	2000
Spacing between rows (cm)	90	100
Spacing between plants (cm)	50	50
Planting density (plants/m^2)	2.2	2.0
Recommended fertilizer rate (N/DAP kg/ha)	96.2	96.2
Potential yield (t/ha)	15.9	18.2

Tab. 2c Description of soil properties used in CROPGRO-Tomato model. LL refers to the soil water content at wilting point and DUL is the soil water content at field capacity. CEC is cation exchange capacity (cmol/kg).

	Layer depth (cm)	Clay (%)	Silt, (%)	Sand, (%)	C_{org} (%)	pH in water	CEC	Total nitrogen (%)	LL	DUL	Bulk density (g/cm³)
1st CH	0-30	34.6	50.4	15.0	2.27	7.7	23.6	0.12	0.052	0.18	1.61
	30-60	35.7	49.1	15.2	2.41	7.6	23.4	0.13	0.073	0.19	1.61
	>60	35.7	49.1	15.2	2.41	7.6	23.4	0.13	0.16	0.35	1.51
2nd CM	0-30	23.3	58.8	18.2	1.59	5.1	20.3	0.11	0.30	0.45	1.31
	30-60	24.1	59.5	16.4	1.96	5.8	19.9	0.10	0.25	0.36	1.37
	>60	22.4	60.0	17.6	1.45	6.4	12.8	0.13	0.28	0.41	1.41

CH - Haplic Chernozems (Praha-Suchdol); CM - sandy-loamy Cambisol (Mochov)

Tab. 5 Cultivar coefficients for CROPGRO-Tomato model, calibrated values for cultivars Thomas F1 and Pálava F1 after updating the cardinal temperatures in SPE file (Boot et al., 2012)

Parameter	Definition	Calibrated Thomas F1/Pálava F1
EM-FL	Time between plant emergence and first flower appearance (Td)	24.4
FL-SH	Time between first flower and first fruit (Td)	3
FL-SD	Time between first flower and first seed (Td)	19
SD-PM	Time between first seed and physiological maturity (Td)	45
FL-LF	Time between first flower and end of leaf expansion (Td)	52
LFMAX	Maximum leaf photosynthesis rate at 30 °C, 350 vpm CO_2, and high light (mg CO_2 m^{-2} s^{-1})	1.36
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm^2 g^{-1})	300
SIZLF	Maximum size of full leaf (all leaflets) (cm^2)	300
XFRUIT	Maximum fraction of daily growth that is partitioned to seed + shell	0.73
SFDUR	Seed filling duration for pod cohort at standard growth conditions (Td)	26
PODUR	Time required for cultivar to reach final pod load under optimal conditions (Td)	28

Td – thermal days

- The cold and wet events during the tomato growing season of 2014 led to high BBCH phase variability, low LAI_{max} 0.5075 $m^2.m^{-2}$ and a low yield of 22.2 $t.ha^{-1}$ (Table 1).
- A beneficial effect of hot and dry events on the tomato fruit was noted during the entire growing period of 2018 (Fig. 5). The CEs in 2018, in comparison to the other years of the study, led to the formation of significantly more LAI_{max} 4.1334 $m^2.m^{-2}$ and yield of 72.1 $t.ha^{-1}$. According to Scholberg et al. (1997), tomatoes growing in open field reached a maximum LAI equal to 3.8 in about 11 weeks after transplanting. However, experimental results show that fruit formation in the tomato cultivar decreases as both extreme temperature and drought frequency increase.
- Drought-heat stress during fruit formation reduces the yield by 30% (each 1°C above 28°C reduced the yield by 10%). Thereby, the greatest differences between the measured and simulated LAI values were recorded in the growing seasons with the highest occurrences of hot-dry and hot-wet events.

4. Conclusion

- During the experimental period, fruit formation in tomato cultivars decreases as both temperature and drought frequency increases.
- Overall, the ability of the CROPGRO-Tomato model to simulate the time-series of LAI/yield for new testing thermophilic cultivars in Elbe lowland conditions was relatively satisfactorily.
- Nevertheless, there were some weaknesses in LAI prediction: in several experiments, the LAI was overestimated, and in other experiments, the LAI was underestimated. Because the comparisons were made using time-series data, the Willmott d index provided well indication of model performance.

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Cultivation of tomatoes in the conditions of climate change in the Elbe lowland, Czech Republic

CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

CASEE Central and South Eastern Europe

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Introduction

Providing people with affordable and cheap food is a serious task for agricultural producers that at present suffer from the impact of climate change. Climate change has a negative influence on the growth of crops, traditional for some regions, but at the same time, the increase of temperature in some countries creates the possibility for the extension of the cultivation areas for thermophilic vegetables. For a better understanding and evaluation of climate change impact on the possibility of the extension of the cultivation areas for thermophilic vegetables in the open field, was performed present research work.

Materials and Methods

- The Thomas F1 variety was used for the research because is an indeterminate tomato cultivar, able to generate high economic returns, especially for small landholders. The crops were planted on experimental lots in the open field, which helped to determine the suitability of the cultivated area of the region for efficient cultivation. During the whole vegetation period, the samples of plants were collected, at regular intervals of time, with measuring necessary parameters in order to determine Leaf Area Index (LAI), BBCH phenological phases and growth analytical characteristics during the period 2014 - 2020 from transplanting to harvest.

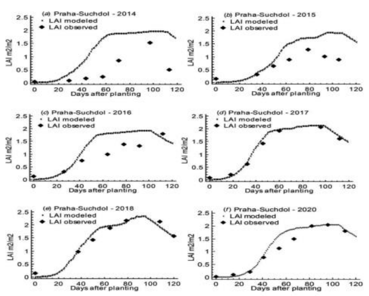
Description of the case study area

- ✓ The study was conducted at 2 sites in the middle Elbe lowland and Praha – Suchdol the central parts of the Czech Republic). This fruiting-vegetable-producing region is characterized by the warmest and driest climatic conditions, where drought stress is often a limiting factor for crops.
- ✓ The agro-climate conditions of the fruiting region ensure the longest growing season and the longest frost-free period with the most productive soil conditions. The planting dates for fresh-market tomato bush cultivars grown under open field conditions correspond to the stable transition of the average daily air temperature through 15°C (season lengths more than 110 days).

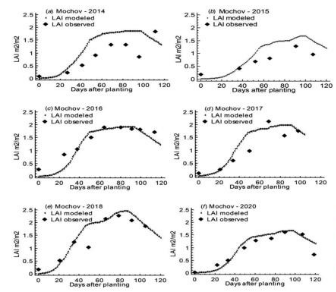
In the frame of the studies was created and calibrated the CROPGRO-Tomato model, included in the Decision Support System for Agrotechnology Transfer (DSSAT) software, for the Thomas F1 indeterminate tomato cultivar. To run CROPGRO model, we used the following 4 basic dataset groups: (1) crop species and cultivar characteristics; (2) meteorological daily data: rainfall (mm), solar radiation (MJm-2d-1), maximum and minimum air temperatures (°C); (3) soil conditions and (4) cultivation technology

Results

Comparison of the simulated Leaf Area Index (LAI) with the observed values of the fresh-market Thomas F1 indeterminate tomato cultivar grown under open field conditions for experimental years 2014 (a), 2015 (b), 2016 (c), 2017 (d), 2018 (e) and 2020 (f) at Praha-Suchdol site.



Comparison of the simulated Leaf Area Index (LAI) with the observed values of the fresh-market Thomas F1 indeterminate tomato cultivar grown under open field conditions for experimental years 2014 (a), 2015 (b), 2016 (c), 2017 (d), 2018 (e) and 2020 (f) at Mochov site.



Sites	2014	2015	2016	2017	2018	2020	2021
Suchdol	22.2	24.5	32.5	40.2	62.8	53.2	30.3
Mochov	25.2	26.9	34.8	50.2	73.4	65.4	34.2

Obtained Thomas F1 harvest t/ha

Conclusion

- The model showed exhibited the highest LAI prediction accuracy. The leaf area development was compared, and although the modelled values were higher than the measured values, they were still within a reasonable range. The model has shown an acceptable range of variations.
- The elaborated simulation model permitted to determine expected growth and development of the crop, based on equations that describe the crop's responses to the specific soil and weather conditions.
- The calibration and evaluation of the CROPGRO Tomato model in this study showed the ability of the model to simulate ongoing field management and climatic impacts on the growth characteristics of tomato. These results can be used for future implementation of proper strategies for crop management and climatic projections

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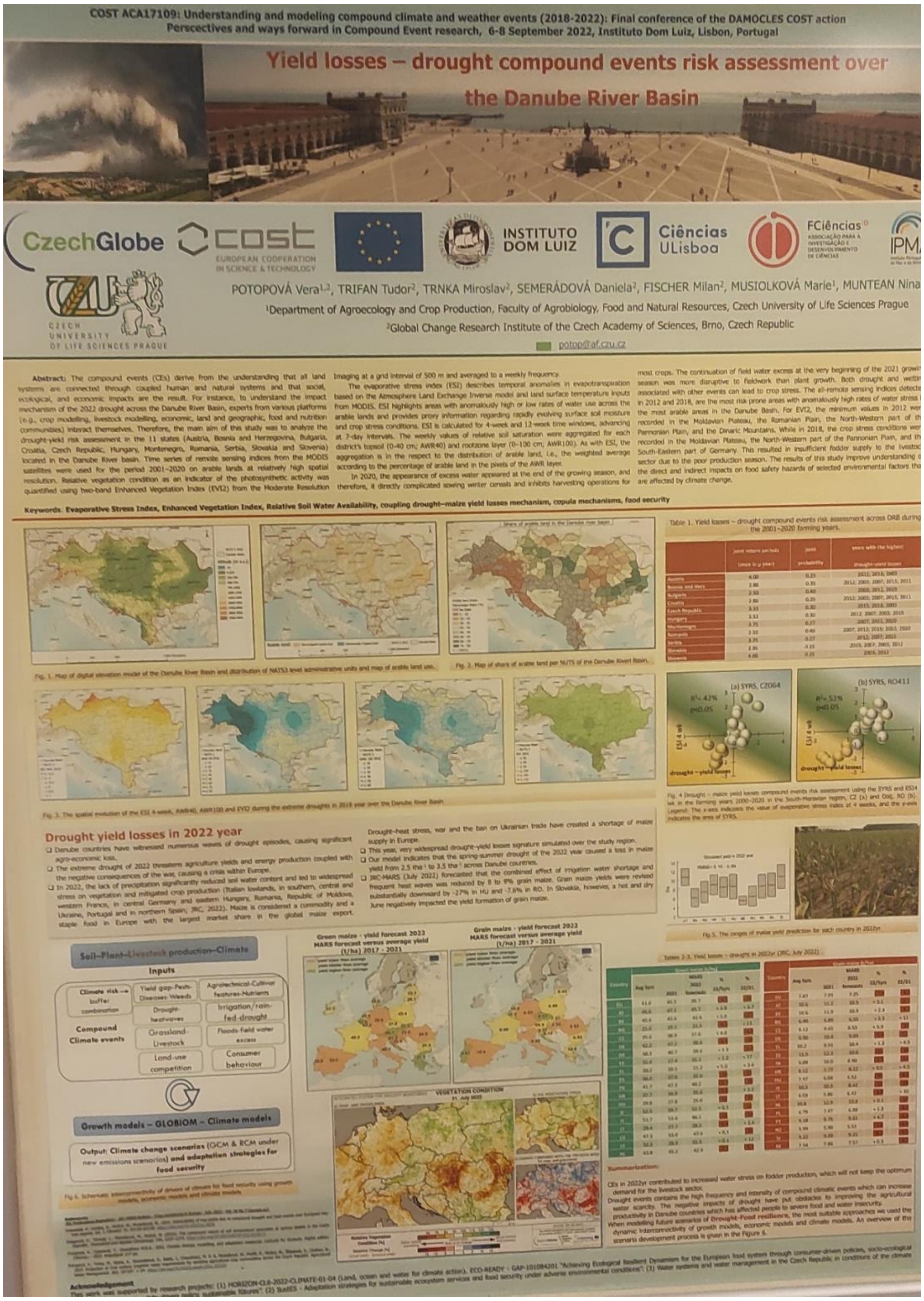
DSSAT


COST ACA17109: Understanding and modeling compound climate and weather events (2018-2022): Final conference of the DAMOCLES COST action
Perscectives and ways forward in Compound Event research, 6-8 September 2022, Instituto Dom Luiz, Lisbon, Portugal
Yield losses – drought compound events risk assessment over the Danube River Basin
CzechGlobe
cost
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Abstract: The compound events (CEs) derive from the understanding that all land systems are connected through coupled human and natural systems and that social, ecological, and economic impacts are the result. For instance, to understand the impact mechanism of the 2022 drought across the Danube River Basin, experts from various platforms (e.g., crop modelling, livestock modelling, economic, land and geographic, food and nutrition communities) interact themselves. Therefore, the main aim of this study was to analyze the drought-yield risk assessment in the 11 states (Austria, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Hungary, Montenegro, Romania, Serbia, Slovakia and Slovenia) located in the Danube River basin. Time series of remote sensing indices from the MODIS satellites were used for the period 2001–2020 on arable lands at relatively high spatial resolution. Relative vegetation condition as an indicator of the photosynthetic activity was quantified using two-band Enhanced Vegetation Index (EVI2) from the Moderate Resolution Imaging at a grid interval of 500 m and averaged to a weekly frequency.
The evaporative stress index (ESI) describes temporal anomalies in evapotranspiration based on the Atmosphere Land Exchange Inverse model and land surface temperature inputs from MODIS. ESI highlights areas with anomalously high or low rates of water use across the arable lands and provides proxy information regarding rapidly evolving surface soil moisture and crop stress conditions. ESI is calculated for 4-week and 12-week time windows, advancing at 7-day intervals. The weekly values of relative soil saturation were aggregated for each district's topsoil (0-40 cm; AWR40) and rootzone layer (0–100 cm; AWR100). As with ESI, the aggregation is in the respect to the distribution of arable land, i.e., the weighted average according to the percentage of arable land in the pixels of the AWR layer.
In 2020, the appearance of excess water appeared at the end of the growing season, and therefore, it directly complicated sowing winter cereals and inhibits harvesting operations for most crops.
Keywords: Evaporative Stress Index, Enhanced Vegetation Index, Relative Soil Water Availability, coupling drought–maize yield losses mechanism, copula mechanisms, food security
Table 1. Yield losses – drought compound events risk assessment across DRB during the 2001–2020 farming years.
Fig. 3. The spatial evolution of the ESI 4-week, AWR40, AWR100 and EVI2 during the extreme droughts in 2018 year over the Danube River Basin
Drought yield losses in 2022 year
Danube countries have witnessed numerous waves of drought episodes, causing significant agro-economic loss.
The extreme drought of 2022 threatens agriculture yields and energy production coupled with the negative consequences of the war, causing a crisis within Europe.
Drought–heat stress, war and the ban on Ukrainian trade have created a shortage of maize supply in Europe.
This year, very widespread drought–yield losses signature simulated over the study region.
Soil–Plant–Livestock production–Climate
Inputs
Climate risk → buffer combination
Yield gap-Pests-Diseases-Weeds
Agrotechnical-Cultivar features-Nutrients
Drought-heatwaves
Irrigation/rain-fed-drought
Compound Climate events
Grassland-Livestock
Floods-field water excess
Land-use competition
Consumer behaviour
Growth models – GLOBIOM – Climate models
Output: Climate change scenarios (GCM & RCM under new emissions scenarios) and adaptation strategies for food security
Green maize - yield forecast 2022 MARS forecast versus average yield (t/ha) 2017 - 2021
Grain maize - yield forecast 2022 MARS forecast versus average yield (t/ha) 2017 - 2021
Summarization:
CEs in 2022yr contributed to increased water stress on fodder production, which will not keep the optimum demand for the livestock sector.
Acknowledgement