CRANFIELD UNIVERSITY

O. SEBEK

CLIMATE RELATED RISKS AND OPPORTUNITIES FOR CITRUS PRODUCTION UNDER CLIMATE CHANGE

SCHOOL OF WATER, ENERGY AND ENVIRONMENT
Environmental Water Management

MSc
Academic Year: 2018–2019

Supervisor: Prof T. Hess, Dr L. Papadimitriou
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This thesis is submitted in partial fulfilment of the requirements for the degree of MSc.

Abstract

Areas that currently grow citrus may lose suitability due to projected changes in fundamental climatic parameters. This study presents a conceptual climate suitability model that simulates potential climate induced effects on citrus fruit growth. Future climate projections were used to map changes in climate suitability across the Mediterranean Basin to investigate the effects of projected changes in temperature, rainfall and other agroclimatic variables. Model simulations indicate significant decrease of frost risk and potential losses virtually all across the study area, while highest concentration is simulated over inland regions with generally higher altitudes predominantly in Spain, Italy, Morocco and Turkey, and marginally over the rest of Europe. This trend is however counter affected by elevated heat stress resulting in suboptimal conditions during the most susceptible stages of fruit growth, i.e. the flowering and fruit set periods, and results in decreasingly suitable conditions for the development of the characteristic rind colouration in anthocyanin-coloured citrus cultivars. Though, as the positive response to projected climate change in marginal and less suitable locations does not outweigh the overall higher suitability in regions with currently suitable climate conditions, it cannot be concluded that citrus production simply shifting to these areas will be an effective response to projected climate change. Adaptation through appropriate management practices will need to compensate for elevated environmental stress on the crop to ensure feasibility of citrus production, though citrus cultivars with less stringent requirements can be expected to challenge economic suitability of more susceptible species.

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List of Abbreviations

GCM	Global Climate Model
GMST	Global Mean Surface Temperature
PPE	Perturbed Parameter Ensemble
RCP	Representative Concentration Pathway
SF	Suitability Factor
TSS	Total Soluble Solids

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Chapter 1

Introduction

Synthesis of evidence for climate change has been published and predominantly accepted by the scientific community (IPCC, 2013a). The Earth system has been successively warmer during the past three decades as compared to any preceding decade since 1850 (Hartmann et al., 2013). In the northern hemisphere, this 30 year period was very likely the warmest of the last 800-1400 years (Masson-Delmotte et al., 2013). The frequency and intensity of daily temperature extremes has increased over large parts of Europe, Asia and Australia (IPCC, 2013b). Future climate projections indicate rising surface temperature under all of the RCP (Riahi, Rao, and Krey, 2011) emission scenarios (Kirtman et al., 2013). Global mean surface temperature change for the period 2016-2035 relative to 1986-2005 is comparable for the four RCPs (in the range of 0.3 to 0.7°C), however the magnitude of projected climate change by mid 21st century and onwards is significantly affected by considered RCP (0.3 to 4.8°C for the period 2081-2100 relative to 1986-2005) (Kirtman et al., 2013; Collins et al., 2013). As global mean surface temperature increases, more frequent, longer duration hot and fewer cold temperature extremes are projected on daily and seasonal timescales over most land areas (Collins et al., 2013).

Understanding potential impacts of climate change on the environment and natural resources, as well as on the fruit and vegetable industry, is challenged by increasing climate variability, recurrent floods and severe droughts, which introduce both direct and indirect effects on the system (Hulme et al., 1999; Edwards et al., 2011). Even in high-technology agricultural areas, climate variability is one of the primary determinants of year to year crop production (Kang, Khan, and Ma, 2009). It needs to be emphasized that the magnitude and direction of climate change impacts will vary spatially and temporarily due to both natural and anthropogenic factors (Tubiello et al., 2002).

To evaluate the impacts, researchers use a wide range of statistical, agro-ecosystem and physical process-based models. A number of studies highlight the potential for adaptation to reduce climate change related costs or increase gains, leaving systems that are slow to adapt more vulnerable (Rosenzweig and Hillel, 1998; Burton and Lim, 2005). Yet, majority of climate change impact research has focused on annual systems rather then long-lived, perrenial cropping systems, that are inherently much slower to adapt.

1.1 Citrus

The group of citrus fruits represents extremely economically important crop with highly nutritive fruits (Hussain et al., 2004). Citrus fruits occupy first rank in the world with respect to total production and international trade value among fresh fruits, and are commercially grown in a broad range of countries around the world (FAO, 2016). Related economical contribution was estimated at more then 10 billion GBP anually while providing millions of jobs around the world across sectors ranging from harvesting to marketing operations (Ladanyia and Ladaniya, 2010).

Classical citriculture achieves highest fruit quality in subtropical areas, as low temperatures and frost hazards restrict expansion to cooler domains. Citrus production is concentrated in many subtropical climates where irrigation requirements challenge management practices (Mediterranean, South Africa, South America, California), and expands to even larger extent in the humid subtropical climates of Brazil and Florida (Spiegel-Roy and Goldschmidt, 1996).

The centre of origin of true citrus fruits is considered to be in South East Asia. While

Tanaka (1954) and Jackson (1991) suggest that citrus fruits may have originated in north-eastern India and Burma, the probable origin of several species and introduction into cultivation started in China (Spiegel-Roy and Goldschmidt, 1996). Tolkowsky (1938) identified the mountainous parts of southern China and north-east India as the likely centre of origin, characterised by the warm rains of summer monsoon with sheltered valleys and southern slopes delivering protection from cold and dry wind.

Climate requirements

In order for citrus fruit to grow and reach maturity, a sufficiently long and warm summer is required, with stringent irrigation requirements in the drier Mediterranean and similar climates with long dry summer periods (Spiegel-Roy and Goldschmidt, 1996). Though citrus is ever-bearing in the tropics, a dormancy period induced by either cool temperatures (Moss, 1969; Hall, Khairi, and Asbell, 1977; Susanto, 1990; Poerwanto and Inoue, 1990; Susanto, Nakajima, and Hasegawa, 1991; Garcia-Luis et al., 1992) or water stress (Cassin et al., 1969; Southwick and Davenport, 1986) and a single, major annual bloom and fruit bearing greatly enhance fruit quality (Rosenzweig et al., 1996). Climatic conditions of subtropical latitudes with definite seasons allow the rhythm of tree growth and blossoming to be controlled by seasonal temperature variations. Humidity in these areas is typically lower and significant daily temperature changes may occur, with occasional severe frosts. The trees experience a cessation of growth throughout winter and start to grow and blossom uniformly in the spring. After a major spring bloom, some subsequent out-of-season blooms may be initiated due to rainfall variability and potential droughts (Reuther, 1973).

The inherent sensitivity of citrus to frost qualifies it among the most sensitive fruit species (Spiegel-Roy and Goldschmidt, 1996). Despite the extreme sensitivity to sub-zero temperatures (Turrell, 1972; Wiltbank and Oswalt, 1987; Huang et al., 1993), major production is concentrated in subtropical areas with low but still real risk of freezing. Hence, regions with consistently cold winters are only suitable for the production of cold-hardy cultivars. However, cultivars with anthocyanin-coloured rind and juice grow successfully in areas with relatively low midwinter temperatures (e. g. Italy), as the natural orange colour is attained only under cool conditions (Spiegel-Roy and Goldschmidt, 1996), while yellow, high-acid cultivars, are widely grown in the tropics (Reuther, 1973). Hence, fairly specific climatic conditions limit the suitability of commercial citrus production to areas that include a cool season with low probability of freezing.

However, both ends of temperature extremes aggravate environmental stress on the crop and represent major constraints on citrus production. Uninterrupted, high temperatures significantly reduce yields, restricting citrus production from very hot areas. The lack of contrasting seasons in tropics combined with high tempretaure and humidity throughout the year adversely affect the quality of the fruit (Spiegel-Roy and Goldschmidt, 1996). Excessively warm periods during the bloom or early fruit set present risk of fruit abscission (Moss, 1970; Reuther, 1973; Ono et al., 1988), and are generally associated with sparse flowering, decreased tree-storage time and increased rind re-greening (Reuther, 1973; Ben Mechlia and J. Carroll, 1989).

Citrus in Mediterranean landscapes

About 20% of global citrus production and 60% of global fresh citrus trade originates in the Mediterranean Basin (CLAM, 2007). Citriculture represents a major segment in the Mediterranean agricultural history, generating significant economic value, with sweet oranges and easy-peeler fruits such as mandarins representing the most frequent production crop. However, other species are widely cultivated in specific areas, i.e. lemons in the Euro-Mediterranean Region, lime in the Near East Region, and grapefruit in Israel and Turkey (Imbert, 2007). The scale of citrus production orchards varies from less than a hectare to several hundred hectares, technologically advanced farms larger than 10ha account for about 80% of net production (Lacirignola and DOnghia, 2009). Spain represents the leading producer with Italy and Egypt ranking second and third, respectively CLAM (2007).

Due to high irrigation and nutrient requirements, majority of citrus trees was originally planted on the most fertile plains and valleys of the mountainous areas up until the mid-twentieth century. The development of technologies capable of drilling and pumping from hundreds of meters deep, and transporting irrigation water by pipes instead of canals, has allowed operational irrigation of regions with conditions originally suitable only for drought tolerant crops, resulting in major opportunities for citrus production to expand to previously unsuitable areas. Ultimately, this trend has led to the current status of citrus representing the most important crop in various regions of the Mediterranean and worldwide (Duarte et al., 2016).

Spatial extent of the study area was restricted to the Mediterranean Basin primarilly due to its particular significance and characteristic subtropical citriculutre. Exact spatial boundary was delineated by latitude and longitude ranges of 30° N to 45° N and 11° W to 40° E, respectively. A subset of major large-scale citrus producing regions was explored in greater detail, concentrating on Valencia (39.4° N, 0.4° W) and Sevilla (37.3° N, 5.9° W), Spain; Nabeul (36.4° N, 10.7° E), Tunisia and Calabria (38.1° N, 15.6° E), Italy.

1.2 Aims and objectives

The aim of the work described in this study is to assess the changes in the suitability of citrus production under projected climate change. To address set aim, three primary objectives were formulated:

1. To develop a conceptual crop model to represent citrus crop response to environmental forcing.

2. To explore areas that presently produce citrus but might lose suitability under projected climate change.

3. To explore areas that show potential suitability for citrus production under projected climate change.

Chapter 2

Methods

The following section provides a detailed description of the structure of the developed model and its internal processes, and introduces used datasets and climate scenarios. The physical basis of climate suitability adopted in this study is provided to illustrate the nature and extent of evaluated influencing factors in order to aid the interpretation of presented simulation results.

2.1 Climate projections

The UKCP18 provides a set of climate projections produced by an ensemble of recent generation climate models including a new 15-member perturbed parameter ensemble (PPE) of global climate (GC) simulations for the period 1900-2100 with respect to the RCP8.5 scenario (MOHC, 2018). Members of the GC3.05-PPE were selected with the aim of excluding implausible simulations to identify a surviving subset of credible projections (Murphy et al., 2018). Components representing the land and atmosphere were defined on a regular latitude-longitude grid at N216 resolution, resulting in approximately 60km horizontal grid spacing at mid-latitudes. Vertical structure of the model was divided into 85 compartments, 30 of which were in or above the stratoshpere, providing improved resolution of middle atmosphere dynamics over most models submitted to CMIP5 (IPCC, 2014; Murphy et al., 2018). The GC3.05-PPE simulations used a wide range of future

CO_2 pathways, one of which was the standard RCP8.5 concentration time series. The rest was selected from a set of 72 different pathways provided by emissions-driven earth system model outputs (Booth et al., 2017) with the intent to subset 15 parameters which are as independent as possible. The simulated range of CO_2 concentration in the year 2099 essentially covered the full range (1-99%) of the probability distribution established within the UKCP18 probabilistic projections with six pathways above the median and nine below (Murphy et al., 2018).

The median global mean surface temperature (GMST) increase by the 2090s is projected to exceed 4°C with respective 10-90% probability range of approximately 3-5.5°C based on projections provided by the UKCP18 probabilistic projections (Murphy et al., 2018). The GC3.05PPE dataset consistently samples the upper 75% of these projections but does not exceed the 99% probability level. However, no future climate simulation populates the lowest 10% of the probability distribution after 2060 (Murphy et al., 2018). Hence, despite the substantial diversity in GMST projections, not all plausible outcomes are captured by the dataset. The 5-95% probability range of GMST warming for the RCP8.5 scenario assessed by the AR5 (IPCC, 2014) describes a range of 2.6-4.8°C for 2081-2100 relative to 1986-2005, corresponding to a 2.7-5.9°C range of the used dataset. Additionally, patterns of ensemble-mean change in clear-sky shortwave radiative heating show relatively significant positive trends over the northern hemisphere continents at middle or high lattitudes, related to projected reductions in snow cover during winter and spring (Murphy et al., 2018).

Three representative time periods were selected to describe the state of the earth system examined within the scope of this study. The first, describing the nearest time period, was regarded as the baseline and spans the years 2009-2019. The other two cover relatively near and a more distant future, representing climate of the 2039-2049 and 2089-2099 periods, respectively. For these time slices, the daily multi-variable dataset produced by the GC3.05-PPE provided input parameters for the citrus climate suitability model developed within this study to assess the spatial and temporal impacts of climate change on citrus climate suitability. Comparison with the baseline period allowed for an evaluation of how climate suitability at each gridpoint might alter due to projected changes in temperature, rainfall and other agroclimatic variables. All members of the ensemble were assigned equal probability, and hence, each examined period was defined by 150 representative years, or 135 fruit growth seasons with respect to the citrus model simulations. Considering the spatial extent of the study area defined by 1827 grid points, this resulted in 739 935 simulated season-location combinations across the three periods.

2.2 Suitability

This study considered the sweet Valencia Orange (Citrus sinensis (L.) Osbeck) as a representative citrus cultivar. Defined suitability therefore reflects climate relationships specific to the species, although similar climate requirements are shared with several other citrus cultivars (Reuther, 1973; Spiegel-Roy and Goldschmidt, 1996).

The architecture of the developed approach was designed with an underlying assumption that each day of the growing season contributes a certain amount to crop and fruit growth, and eventually leads to advancement in the phenological sequence. Individual contribution of a given day was scaled with respect to its deviation from defined optimum conditons. Suboptimal conditions consequently decreased the simulated suitability for citrus growing by a factor proportional to to the divergence from the appropriate limit. For this purpose, empirical suitability factor (SF) was derived to quantify the deviation based on specified functional relatioships. The value of SF ranges from 0 to 1, the latter corrensponds to a perfect match with defined optimum environmental conditions. Any decrease in SF can be interpreted as a degree of environmental stress on the plant, representing a major constraint on potential fruit growth and net production. In fact, four different SFs relating to the sources of simulated environmental stress (fruit set, frost damage, rain damage, rind colour development) were produced with each model simulation.

Hence, suitability defined within the scope of this study represents the combined effect of each simulated environmental process on citrus fruit growth and maturation. Though major plant-environment interaction dynamics were conceptualised in the developed model, it needs to be aknowledged that only a limited range of environmental factors and parameters was considered, i.e. the model assumes optimal irrigation throughout the lifecycle of the modelled crop and does not attempt to simulate effects of different planting densities or conditions of the crop such as tree age or fertilizer and pesticide use. Due to the full irrigation assumption, simulated suitability does not reflect potential constraints on citrus production related to water availability.

2.3 Model design

A key part to conducting this study originated from the successful development of a conceptual model with a sufficient degree of predictive ability. The model needed to set a reasonable balance of the simplification of key environmental processes which influence citrus fruit growth. The simulation run time of an instance of the developed model also needed to provide results in a reasonable time frame, aknowledging the extent of used data. The underlying assumption of daily contributions to plant development and fruit growth under optimal or suboptimal conditions, with the inclusion of potential extreme effects, set a foundation for the architecture design. The data requirements were therefore limited to fundamental drivers of the plant-environment interaction, which aligned with the premise of considering only conventionally available meteorological variables.

The purpose of the model was to simulate potential effects of presented climatic variables on a specified citrus cultivar during the fruit growth period with respect to the subtropical regime. Internal routines and defined functional relationships, derived with respect to specific citrus climate requirements to characterise the crop response to presented environmental factors, are analogous to these reported by Cooper (1965), Chang (1968), Moss (1970), Hall, Khairi, and Asbell (1977), and Lomas and Burd (1983). Several empirical relationships were inspired by a simple citrus model implementation de-

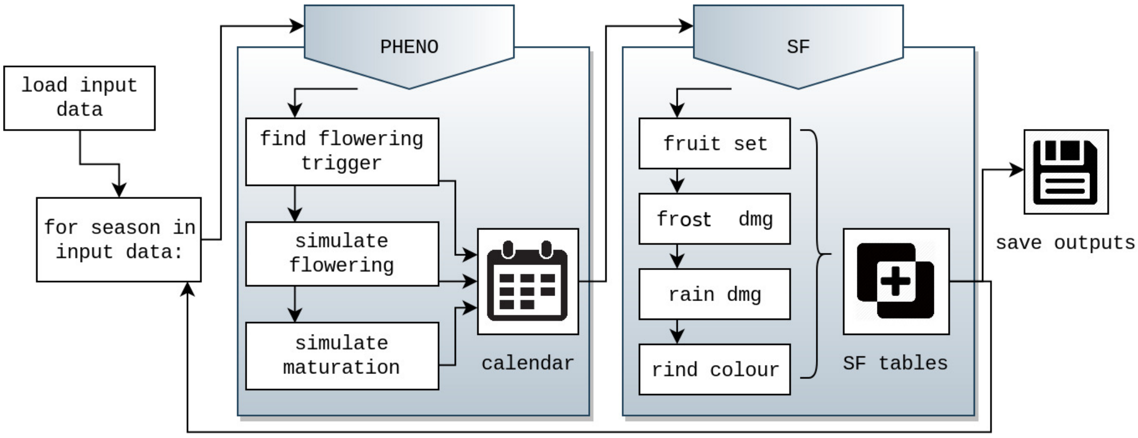

Figure 2.1: Model workflow diagram

scribed in Ben Mechlia and J. Carroll (1989). Linear functions with specific temperature range optimum for the simulated plant process typically define the functional relationships, temperatures exceeding above or below that range result in decreased suitability. Data required to run the model relate primarily to climate (daily minimum, mean and maximum temperature, daily precipitation totals and daily solar shortwave radiaton flux) along with a specification of management practices such as frost protection of the trees. The modelling workflow illustrated on Figure 2.1 describes the two successive simulation stages:

1. Input climate dataset is analysed to determine the phenological sequence of the modelled crop for current simulation period, i.e. the start and end of the dormancy, prebloom, flowering, early fruit set and maturation periods, based on defined triggering conditions.

2. The model simulates potential climate induced effects during each phenological stage to assess suitability for crop growth and fruit production, internal routines evaluate rind colour development and simulate potential frost or rain damage.

Setting the phenological calendar

In the first stage of the simulation, the model analyses the input dataset to generate plant phenological calendar for the current simulation period based on defined triggering conditions and functional relationships. The simulation is initiated in winter to ensure the phenological sequence follows the natural order: dormancy, prebloom, flowering, fruit set, fruit growth and maturation. The model first identifies the date of the onset of flowering. The triggering condition is based on exceeding a dynamic threshold of 5 day moving average minimum daily temperature controlled by the amount of solar radiation for the given day, implemented as (2.1) (Ben Mechlia and J. Carroll, 1989). The higher the radiation load, the lower the temperature threshold required to trigger flowering. The averaging period was applied to smooth out the high frequency of daily temperature variations while preserving information about any significant trends relevant to the phenology. First occurence of the trigger sets the date of flowering, with prebloom period preceeding it by 30 days (Moss and Muirhead, 1971). The duration of the flowering period is implemented as a function of daily mean temperature, (2.2) determines the number of days from the onset of flowering to the start of the early fruit set period (Reuther, 1973; Lomas and Burd, 1983), which has a fixed duration of 50 days (Jones and Cree, 1965).

$$thr_{Tmin} = \begin{cases} 2, & rss > 30 \\ 21, & rss < 2 \\ -1.05 * rss + 33.7, & otherwise \end{cases} \tag{2.1}$$

$$n_{flow} = \begin{cases} 20, & T_{mean} > 23 \\ 75, & T_{mean} < 10 \\ -4.23 * T_{mean} + 117.3, & otherwise \end{cases} \tag{2.2}$$

$\mathbf{thr_{Tmin}}$ = daily minimum temperature threshold [°C]

$\mathbf{T_{mean}}$ = daily mean temperature [°C]

rss = daily net surface downward shortwave radiaton flux [Wm^{-2}]

$\mathbf{n_{flow}}$ = flowering time [days]

Following the fruit set period, maturation of the fruits is conceptualised by simulating the development of the total soluble solids to acid (TSS:acid) ratio usually reffered to as the maturity index Reuther (1973). First, the time required to reach TSS:acid ratio of 6:1 is determined with respect to (2.3). Then, following the beginning of the maturation processes, (2.4) provides daily increments to that ratio with respect to daily mean temperature until it reaches full maturity and the date of first possible harvest is set (Rasmussen et al., 1966; Ben Mechlia and J. Carroll, 1989).

$$n_{mat} = \begin{cases} 170, & T_{mean} > 27 \\ 380, & T_{mean} < 13 \\ -15.0 * T_{mean} + 575.0, & otherwise \end{cases} \tag{2.3}$$

$$i_{mat} = \begin{cases} 0.03, & T_{mean} > 30 \\ 0.09, & T_{mean} < 2 \\ 0.004 * T_{mean} - 0.025, & otherwise \end{cases} \tag{2.4}$$

$\mathbf{n_{mat}}$ = initial fruit maturation time [days]

$\mathbf{i_{mat}}$ = daily TSS:acid increment [-]

Determining potential effects

Potential effects of daily temperature ranges on the crop are addressed by two parameters. The first represents the relationship with optimum daily mean temperature range during the fruit set period and is defined by (2.5) derived with respect to the findings of Moss and Muirhead (1971), Hall, Khairi, and Asbell (1977), and Ben Mechlia and J. Carroll (1989). Then, the marked negative effect of excessively high temperatures is determined from (2.6), which is subsequently related to (2.7) that evaluates the effect of prebloom temperatures and thus represents the relationship with temperatures during fruit anthesis (Jones and Cree, 1965). With this convention, high temperatures cause more pronounced impacts if they follow flowering that took place under cool weather when compared to warm conditions, allowing for a degree of adaptation. The higher the value of either of the frost effect parameters, the more significant environmental stress is simulated by the model. Both parameters are ultimately combined into the fruitset SF presented with model outputs.

$$\triangle SF_{Tmean} = \begin{cases} 0.06 * T_{mean} - 1.8, & T_{mean} > 27 \\ -0.04 * T_{mean} + 0.9, & T_{mean} < 22.5 \\ 0, & otherwise \end{cases} \tag{2.5}$$

$$\triangle SF_{Tmax} = \begin{cases} 0.5, & T_{max} > 49 \\ 0, & T_{max} < 38 \\ 0.045 * T_{max} - 1.72, & otherwise \end{cases} \tag{2.6}$$

$$f_{preb} = \begin{cases} 1, & T_{mean} < 15 \\ -0.03 * T_{mean} + 1.5, & otherwise \end{cases} \tag{2.7}$$

$\boldsymbol{\Delta}\mathbf{SF_{Tmean}}$ = suitability factor related to optimum mean temperatures [-]

$\boldsymbol{\Delta}\mathbf{SF_{Tmax}}$ = suitability factor related to optimum maximum temperatures [-]

$\mathbf{f_{preb}}$ = prebloom mean temperature coefficient [-]

Frost related effects and potential damage on citrus are defined by an exponential functional relationship with daily minimum temperature, meaning moderate temperatures cause marginal damage but with further decreases the relative damage increases exponentially, which is in agreement with the findings of Cooper (1965), Young (1977), and

Yelenosky and Young (1977). Distinction between dormant, cold hardened and actively growing trees is made to account for variable vulnerabilities at different phenological stages and with different management regimes (2.8). Magnitude of the impact depends not only on the absolute minimum temperature reached, but also on the continuous duration of low temperatures, which is addressed by the frost persistance factor derived from maximum temperature on the following day (2.9), which then adjusts the final simulated frost damage (Ben Mechlia and J. Carroll, 1989). Frost damage influences the simulated suitability at all stages of crop development, and thus reflects both shoot and leaf, as well as flower and fruit damage.

$$\triangle SF_{frost} = \begin{cases} e^{(-0.52*T_{min}-4.6)}, & if \text{ dormant} \\ e^{(-0.42*T_{min}-3.2)}, & if \text{ protected} \\ e^{(-0.34*T_{min}-2.6)}, & if \text{ not protected} \end{cases} \tag{2.8}$$

$$f_{fpers} = \begin{cases} \begin{cases} 0, & T_{max} > 15 \\ 1, & T_{max} < 2 \\ -0.07*T_{max}+1.15, & otherwise \end{cases}, & if \text{ protected} \\ \\ \begin{cases} 0.2, & T_{max} > 18 \\ 1, & T_{max} < 7 \\ -0.07*T_{max}+1.5, & otherwise \end{cases}, & if \text{ not protected} \end{cases} \tag{2.9}$$

$\mathbf{\Delta SF_{frost}}$ = suitability factor related to frost effects [-]

$\mathbf{f_{fpers}}$ = frost persistance coefficient [-]

Potential constraining effects of rainfall during the flowering and fruit set periods, including mechanical damage to flowers and limitation of pollination, are represented in the model by the rain damage factor derived as (2.10). Analogous relationship was used to determine rainfall related constraints in (Ben Mechlia and J. Carroll, 1989). Days with rainfall amounts exceeding 3 mm/day were considered to result in suboptimal conditions and introduce limiting effects on flowering and growth of the fruit.

$$\triangle SF_{rain} = \frac{n_{rain}}{n_{tot}} \tag{2.10}$$

$\mathbf{\Delta SF_{rain}}$ = suitability factor related to rainfall effects [-]

$\mathbf{n_{rain}}$ = days with rainfall > threshold [-]

$\mathbf{n_{tot}}$ = total days [-]

The development of rind colouration and attainment of the characteristic orange pigment of oranges and other anthocyanin-coloured cultivars is determined from a functional relationship described by (2.11), which relates daily increments to the rind colour index (Reuther, 1973) to a required daily mean temperature range with respect to the findings of Stearns and Young (1942), Erickson (1960), and Young and Erickson (1961) and includes regreening of the fruit under the condition of high daily temperatures.

$$SF_{rind} = 0.1 * (n_{opt} - n_{subopt}) \tag{2.11}$$

$\mathbf{SF_{rind}}$ = suitability factor related to attained rind colour [-]

$\mathbf{n_{opt}}$ = days within optimum mean temperature range [-]

$\mathbf{n_{subopt}}$ = days outside optimum mean temperature range [-]

2.4 Interpretation of simulation results

Environmental factors decribed above ultimately defined climate suitability of a given location for successful fruit growth and production of the modelled crop, represented by the derived Suitability Factor. When presenting model outputs in a combined form, each modelled process contributed to the overall SF score in a multiplicative manner, with the exception of rind colour, which was excluded and is presented separately since it doesn't directly relate to the quality of the fruit (Reuther, 1973; Spiegel-Roy and Goldschmidt, 1996). With this convention, model runs with multiple sources of significant environmental stress generated more profound decrease in the overall SF score.

In order to verify the performance of the set of model routines and functional relationships and validate simulated responses to presented environmental factors, model simulation results for the baseline period were used to identify areas with currently thriving large-scale citriculture to express a measure of its predictive accuracy by comparing the extent and location of areas with high simulated SF scores against current citrus producing regions in the Mediterranean Basin. Though the resolution of the climate dataset allowed only for a relatively large-scale analysis, the grid point spacing described the study area with sufficient detail for a clear comparison. The simulated SF scores used for this comparison were represented by the median combined SF value determined from the set of 135 fruit growth seasons modelled for each grid point to address the combined effect of each simulated process by a measure of its central tendency without being significantly influenced by outliers, which relate to potential occasional season with severe frost or heat stress, to provide a better idea of a typical value which provides suitable characteristic of the given location.

Furthermore, since model outputs retain information about the degree of influence of each modelled process on the final SF score, model simulation results were examined in greater detail with respect to each individual simulated process affecting the modelled SF score to provide specific information and reveal the driving forces behind identified general trends. Hence, analogous analysis was performed on the most sensitive parameters separately. In addition to the spatial analysis of the median SF score, variability of the simulation results dataset was represented by the 10-90 percentile range to illustrate a degree of sensitivity to seasonal variations in environmental conditions and complement information provided by median SF scores. Additionally, areas with low 10-90 percentile range values indicated that simulated suitability of the given location was insensitive to used GCM climate projection.

Analysis of simulated climate suitability for the subset of large-scale citrus producing regions was similarly carried out with respect to each simulated process separately to allow for a clear identification of the major sources of projected environmental pressures on citrus climate suitability. However, model simulation results were not represented by a single characteristic value, but the full frequency distribution of the produced 135 member dataset is presented with histogram plots, enabling detailed analysis of simulated patterns and trends. Each simulated citrus fruit growth season contributed equal probability to presented distributions, which consequently illustrate derived probabilities of simulated SF score levels.

Chapter 3

Simulation results

Model simulation results for each climate scenario comprised 135 values of the derived Suitability Factor (SF) representing the set of simulated fruit growth seasons analysed for each grid point. To visualize the produced dataset, median values of the combined SF plotted over a basemap instance on a grid defined by modelled locations are presented on Figure 3.1a. Ideally, regions with climate suitable for the production of the simulated citrus crop should rank high on the SF scale ranging from 0 to 1, the latter corresponds to theoretically optimal environmental conditions.

Model results for the baseline period successfully reproduce regional patterns in climate suitability for citrus production in the Mediterranean Basin (Figure 3.1a). Highest SF values observed for coastal parts of Spain, Italy, Morocco, Tunisia, Libya, Egypt and other coastal areas are consistent with regions with thriving citriculture Spiegel-Roy and Goldschmidt (1996). The characteristic vulnerability of citrus to frosts is well illustrated by low SF values at higher altitudes or further away from the warm coastal areas. Consequently, the baseline scenario was established as a reference period future projections are put in relation to.

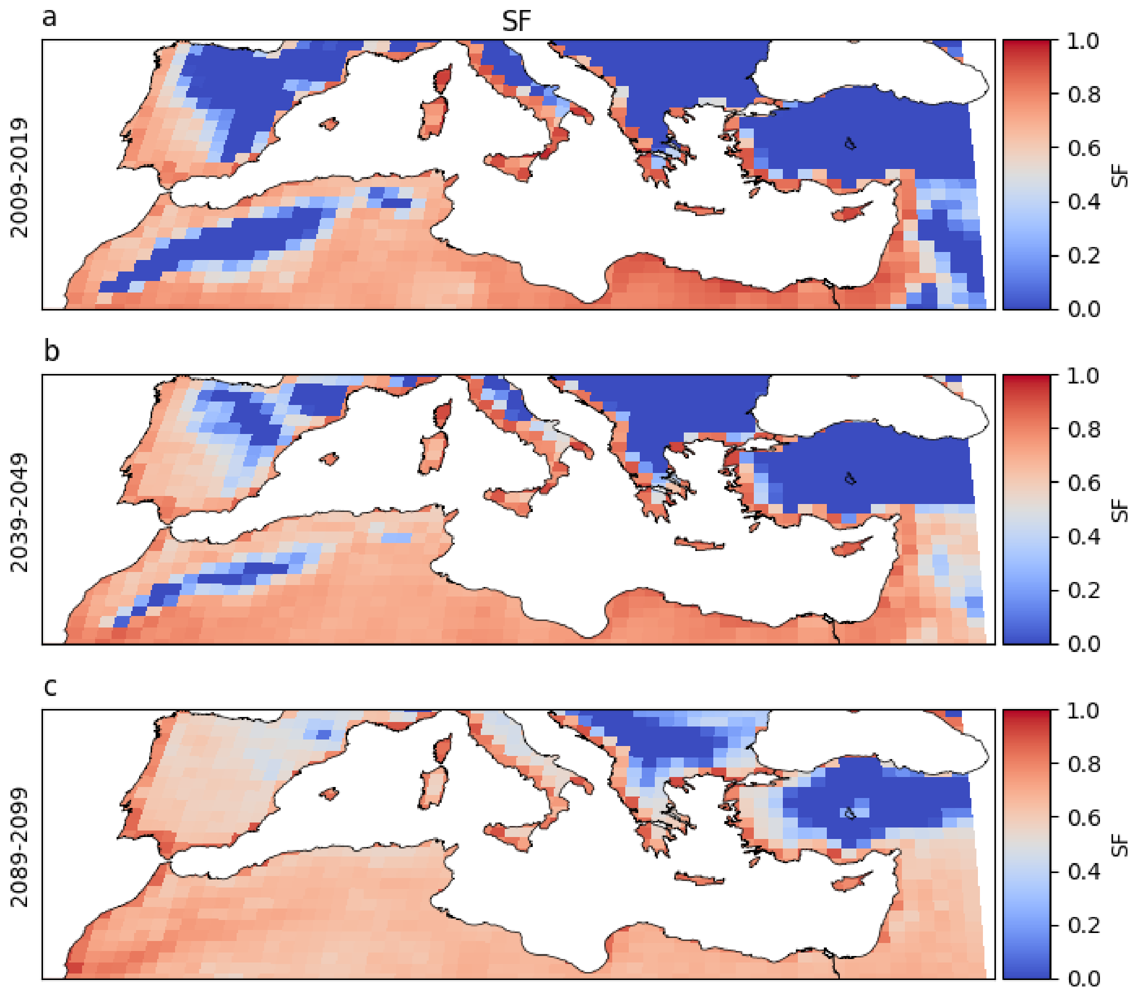

Figure 3.1: Median simulated combined Suitability Factor (SF) for the baseline (a) and future (b, c) climate scenarios.

3.1 Future climate projections

Model projections for the two future climate scenarios were used to produce SF maps comparable to the baseline period and are presented on Figure 3.1b and c. Simulation results indicate two general trends in the response to changing climate. First, the intensity of unfavourable conditions in areas with severe climate constraints on potential citrus production over Europe, Morocco and Turkey seem to be decreasing in general. Contrastingly, suitability of areas with values in the medium and higher range progressively deteriorates with future climate change.

To provide greater insight into the driving forces behind those trends, gridded median values of the frost and fruitset SF for each period are presented on Figure 3.2. Similarly, high SF values can be interpreted as a good match of simulated climate conditions with citrus climate requirements with respect to the presented process. While the simulated effects of projected climate change result in a significant reduction of frost related constraints across the entire study area, inland regions with typically higher elevation are most positively affected, as the frost risk in warm coastal areas is generally much lower for all considered climate scenarios. On the other hand, however, projected decreasing trend in climate suitability for optimum fruit setting counteracts the positive effect of lower frost risk and introduces a major pressure on climate suitability in most regions. The spatial variability of this response is relatively uniform and the intensity relates to suitability levels simulated for the baseline period.

Subsequently, to complement information derived from simulation outputs presented on Figure 3.2, a measure of the variability of simulated SF scores was analysed with respect to each modelled process. The 10-90 percentile range presented on Figure 3.3 characterised locations where simulated suitability was most sensitive to seasonal variations in environmental conditions with respect to each presented environmental factor. In agreement with identified trends, highest variability is observed in regions where frost risk is the dominant constraint on potential citrus production. Significantly higher variability in the frost damage factor as opposed to the fruit set SF agrees with the characteristic

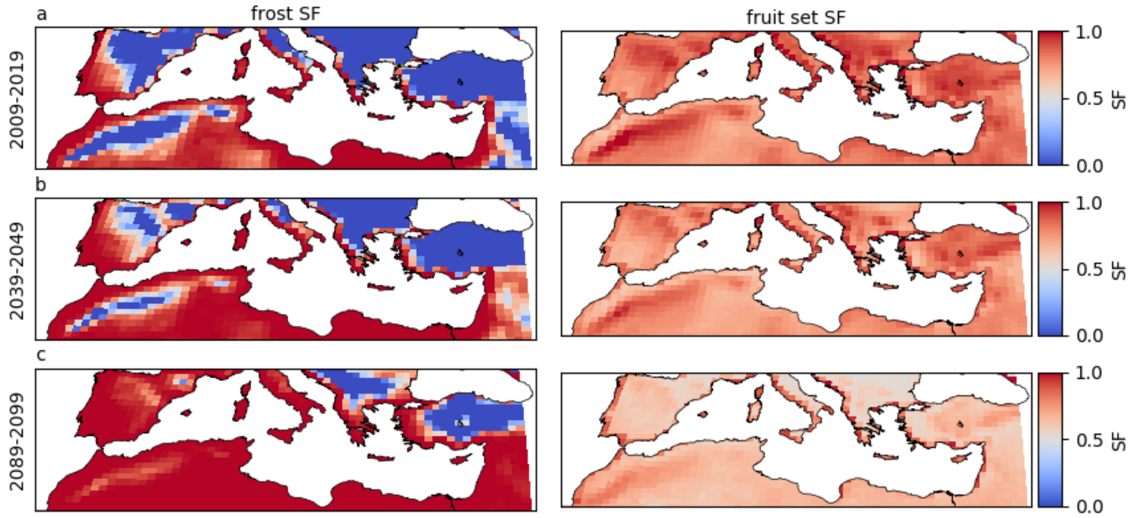

Figure 3.2: Median simulated Suitability Factor (SF) with respect to frost damage (left) and fruit set (right) for the baseline (a) and future (b, c) climate scenarios.

susceptibility of citrus to these conditions.

Projected changes

To investigate areas where climate change projections suggest a reduction in environmental stress constraining potential suitability for citrus production and thus that benefit from the projected climate change, differences of median simulated combined SF for the two analysed future scenarios are presented on Figure 3.4. It needs to be noted that Figure 3.4 illustrates changes and not overall SF scores, and intends to aid the interpretation of previously presented model simulation results. Value range of the colour scale was selected with the intent to allow for clear illustration of both negatively and possitively affected areas. The magnitude and spatial extent of simulated change is relatively low for the near future climate scenario, highest rate of positive change is simulated in areas with presently unsuitable conditions predominantly relating to high frost risk, however this trend is considerably intensified in the case of the more distant time period, where the adverse effects of elevated heat stress similarly start to introduce significant pressures on citrus production across regions with formerly higher suitability.

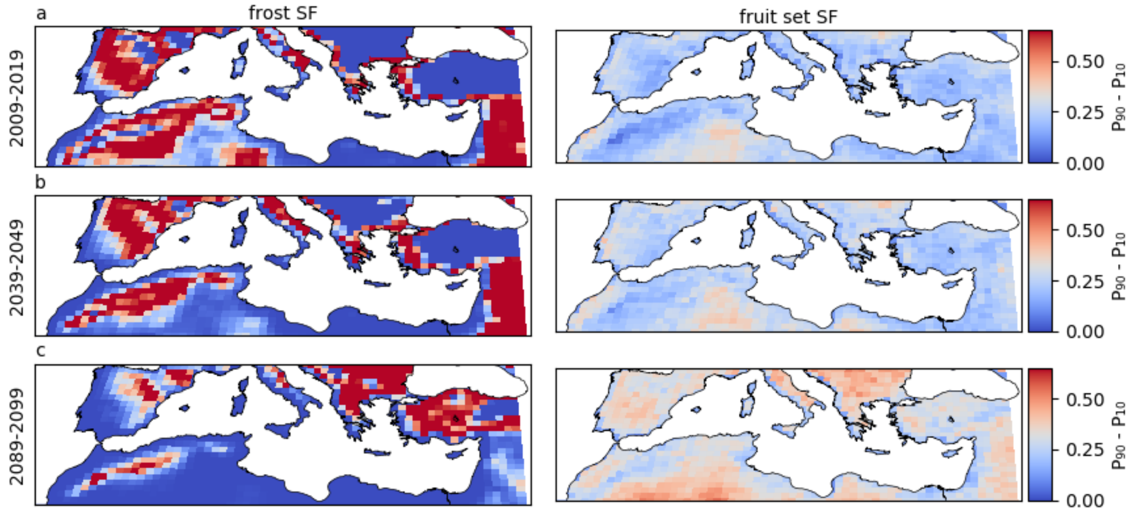

Figure 3.3: 10-90 percentile range of simulated frost effects SF (left) and fruit set SF (right) for the baseline (a) and future (b, c) climate scenarios.

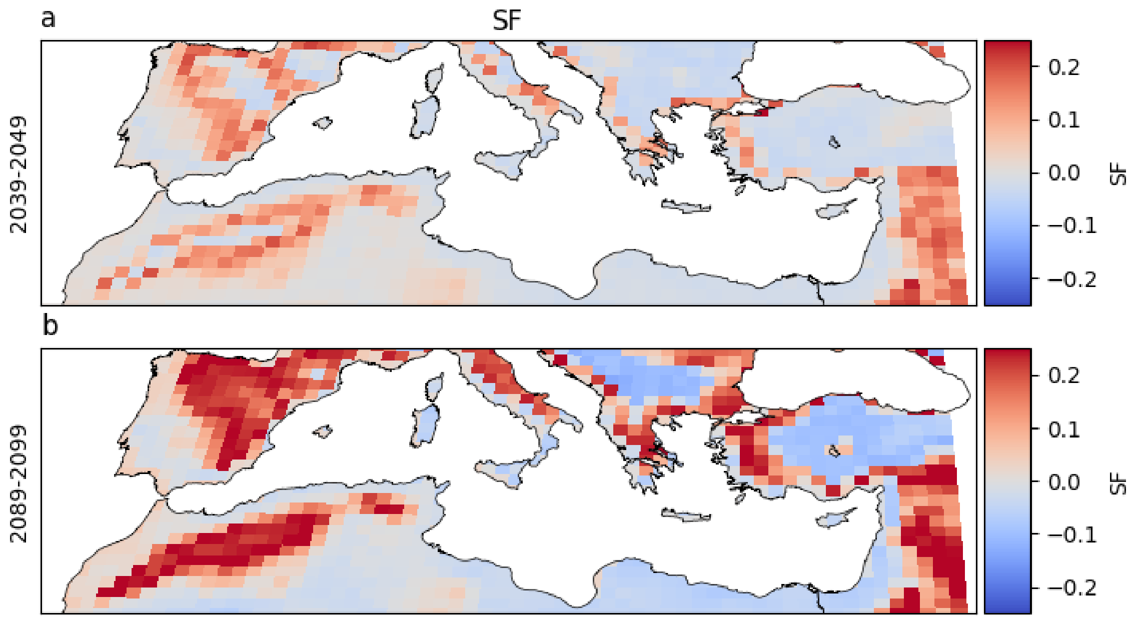

Figure 3.4: Difference of median simulated combined Suitability Factor (SF) for the two future scenarios (a, b) with respect to baseline.

Major citrus-growing regions

Model simulation results for the subset of current major citrus producing regions, represented by frequency distributions of simulated SF scores for the three analysed periods, are presented on Figure 3.5. While the rain and frost damage factors are very insensitive to the considered climate change scenario and represent minimal sources of environmental stress in these regions, significant variations in fruitset, and particularly in the rind colour, parameters are projected consistently across all selected locations, while the magnitude of change in the simulated response varies for the two climate scenarios. In the case of the more distant time period, model simulations very confidently suggest the projected climate will not be able to provide suitable conditons for the developent of the characteristic rind colouration. Both climate scenarios illustrate increasing probability of suboptimal fruit setting conditions as a result of elevated heat stress. Consistency in the simulated response across all selected locations substantiates the developed approach.

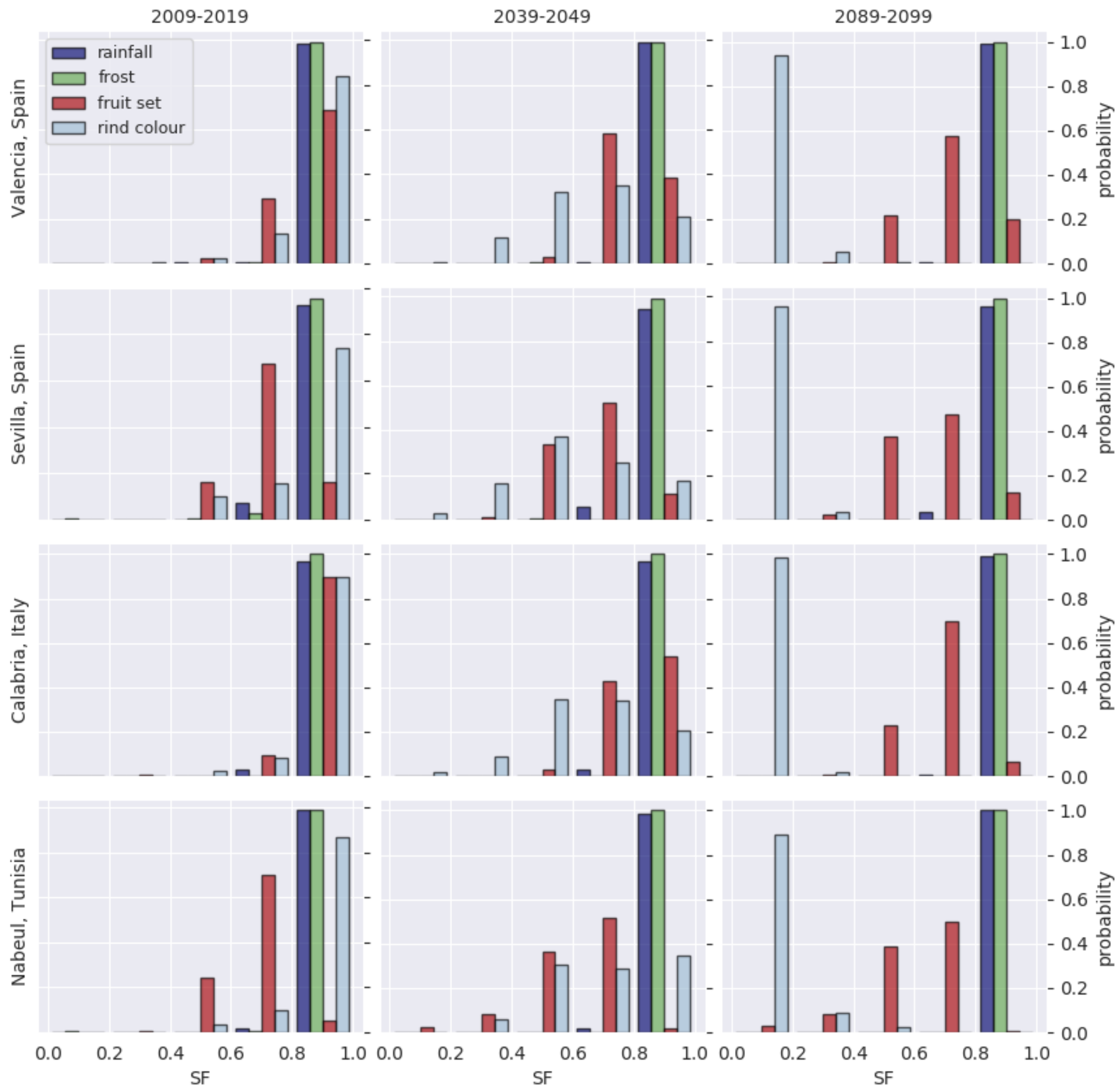

Figure 3.5: Frequency distributions of simulated Suitability Factor relating to each modelled process with respect to estimated probability for Valencia and Sevilla, Spain; Calabria, Italy and Nabeul, Tunisia regions for the baseline (left) and future (middle, right) climate scenarios.

Chapter 4

Discussion

Following section provides discussion of simulation results and relates identified patterns and trends to consensus in published literature. Methodological limitations are characterised to express constraints of applied research design and address generalizability and applicability of derived findings.

4.1 Simulation results

The set of model results addresses the fundamental question of climate suitability from the perspective of multiple influencing factors, allowing for a detailed investigation of the dynamics of the interaction. General patterns and trends identified from the analysis of model simulations, relating model outputs for the future climate scenarios to the baseline period, are consistent for regions of similar character. The positive direction in simulated frost related stress on citrus, which is projected to decrease significantly under projected climate change, is counter affected by elevated heat stress resulting in suboptimal conditions for citrus flowering and fruit set. The degree of variation in these two parameters ulimately defines the final simulated suitability, separating regions with a projected negative response from regions that are positively affected. The prevalent effect of elevated heat stress represents a major concern particularly for regions with currently suitable conditions, suggesting citrus in these regions is currently at the threshold of climate suitability. Similarly, one of the key signals identified by model simulations relates to the implications of elevated heat stress not providing suitable conditions for the development of the characteristic rind colouration, which suggests potential higher post-production re-greening requirements. Plant adaptation and management factors might help mitigate the severity of the impact, however citrus cultivars with less stringent requirements might prove favourable over more susceptible species.

The ability to investigate each environmental factor individually provides insight into the dynamics and driving forces of the system, and enhances potential quality and detail of derived interpretations and conclusions. Projections of frost related constraining effects indicate significant decrease of frost damage and potential losses virtually all across the study area, while highest concentration is simulated over inland regions with generally higher altitudes predominantly in Spain, Italy, Morocco and Turkey, and marginally over the rest of Europe. These areas were simultaneously described by highest sensitivity to seasonal climate variability, which supports the identified gradual shift to increasingly suitable conditions. Considering the extreme sensitivity of citrus to frosts, this suggests a significant reduction in climate-induced stress on the crop under future climate change. However, projected effects of climate change, and specifically higher temperatures, simultaneously result in alterations to the timing of advancement in the phenological sequence and generally cause the flowering and fruit set periods to trigger earlier, when the risk of sub-zero temperatures is principally higher. Nonetheless, the trend in increasing simulated suitability in marginal regions identified on Figure 3.1 is primarilly related to this net positive effect. Conversely, however, elevated heat-induced stress predominantly during flowering and fruit set, the two most vulnerable periods of fruit development, resulted in increasingly suboptimal climate conditions and counteracted the effects of lower frost risk. Analysed projections indicate a gradual global increase of heat stress over the two future climate scenarios, which ultimately explains the contrasting trend of decreasing suitability presented on Figure 3.1. Seasonal climate variability introduced significantly lower effect on optimum fruit setting when compared to the frost risk factor, which illustrates the characteristic extreme susceptibility of citrus to frosts and is clearly represented on Figure 3.3.

The signal derived from presented model projections suggests that if climate change adaptation was to follow these trends, it might materialize in citrus growing shifting or expanding inland, further away from the warm coastal areas, potentially to higher altitudes, particularly in the case of Spain and Morocco. With a significant decrease of simulated frost risk, identified regions are projected to be increasingly able to provide favourable conditions for successful citrus growth and fruit production. However, the intensity of change is relatively insignificant, which is particularly true for the 2039-2049 period, and thus this direction in climate change effects on potential citrus climate suitability represents a considerably long-term process. Furthermore, due to citrus orchards being a perrenial system, adaptation to climate change through planting and breeding opportunities seem limited in the short-term. As potential expansion of citrus as a result of lower probability of frost events is counteracted by the effects of elevated heat stress, the ratio of those factors will ultimately define the net change in citrus climate suitability under climate change.

Gradual decrease of the simulated fruit set SF across the subset of analysed curent citrus producing regions can be attributed to the aggravated heat stress resulting in suboptimal fruit setting conditions, potentially leading to fruit abscission. As temperature ranges in these areas typically tend to approach the higher end of the optimum temperature range, any future projected increase results in exceeding the defined threshold and consequently leads to suboptimal conditions for fruit development. Interestingly, model outputs very clearly suggest climate of the 2089-2099 period does not provide suitable conditions for the development of the characteristic rind colouration, irrespective of the particular analysed citrus producing region. This phenomenon was not represented in the results presented on Figure 3.1, as attained rind colour is not directly correlated with fruit quality and maturity. However, related impact on marketability can be presumed to significantly influence post-production management practices in order to meet marketable fruit quality requirement standards.

4.2 Published literature

Analysis of climate change effects on Valencia oranges in high-producing areas across the southern United States (Tubiello et al., 2002) utilizing outputs of 2 GCMs over two future time periods to drive a conceptual citrus production model (Ben Mechlia and J. Carroll, 1989) provided an opportunity to support interpretations and conclusions formulated within this study. Reported results identified great benefit to simulated fruit produciton under projected climate change, resulting in 20-50% yield increase while required irrigation water decreased. However, these results relate to the CO_2 fertilization processes driven by increased temperatures which weren't conceptualized in the developed model. They represent a potentially significant driver determining the suitability for citrus production, which might alter the direction of influence on final suitability. Similarly, Rosenzweig et al. (1996) concluded that a decline of citrus production is projected with respect to an increase in mean air temperatures unless increased atmospheric CO_2 concentration happen to counteract that trend. The CO_2 fertilization effect in citrus is emphasized to represent a crucial determinant of whether the negative impact of the accompanying increase in temperature will be the dominant factor in determining climate suitability. However, significant uncertainty is related to the degree of the CO_2 fertilization effect in agriculutural fields when compared to controlled experiments, resulting in yield changes ranging from -30 to +20% based on the assumed strength of the simulated CO_2 response (Tubiello et al., 2002).

Annual variations in yield and crop losses due to frost damage were reported to decrease by 65% on average in 2030 and by 80% in 2090 (Tubiello et al., 2002), which is in agreement with the trends identified by the model developed within this study. Decrease in frost risk and improvements in yield were similarly reported by Rosenzweig et al. (1996) when analysing US citrus production under climate change utilizing the identical modelling approach (Ben Mechlia and J. Carroll, 1989). Additionally, Tubiello et al. (2002) investigated the potential for northward expansion of citrus production to higher altitudes, and though production in nothern marginal sites experienced higher yields under projected climate change, lower water availablity, higher risk of crop losses due to frosts and overall lower fruit yield compared to the southern sites prevailed irrespective of the climate scenario. This result is in agreement with the findings of Rosenzweig et al. (1996) and similarly, analogous signal was identified by the presented study, as positive response to projected climate change in marginal and less suitable locations does not outweigh the overall higher suitability in regions with currently suitable climate conditions.

4.3 Methodological limitations

Assessment of the suitability of a given region for the production of a specified crop, particularly the effect of meteorological variability on suitability, represented the primary goal in developing this model. Hence, other factors were parametrised, held constant or not included in the simulations reported here as the purpose was to examine the role of climate alone in determining suitability. The developed model achieves a good balance of relative simplicity, predictive ability and input data availablity. It is a conceptual representation of the dynamic interaction between citrus fruit growth and local climatic conditions. Defined routines and functional relationships have associated uncertainties, however since relative suitability is the primary information communicated with this type of model, fine-tuning and slight modifications of the defined functions for a better representation of a particular instance seem inappropriate. Hence, information communicated through model outputs intend to indicate a qualitative mesure of simulated climate suitability rather than a deterministic value with physical meaning. Ultimately, clear patterns and trends are identifiable in model simulation outputs, consistent across the study area, which suggests a reasonable representation of the system and substantiates derived interpretations and conclusions.

Uncertainty introduced by the design structure of the model principally relates to the simplifications and empirical parametrisations defined within the model, which intend to represent the relevant relationship with a reasonable accuracy/simplicity ratio. The model assumes the simulation occurs in a mature orchard with no constraints related to the state of the trees, not considering potential effects of tree age or diseases. Soil characteristics and the degree of management undoubtedly influence potential productive yield and quality of the fruit of a given orchard, however the simulations reported here do not attempt to represent these conditions due to the complexity and uncertainty associated with parametrisation of such relationship. Pest and disease factors are similarly not included in the modelling process as these are not easilly obtainable and verifiable on the scale of the study. With the assumption of full irrigation, the model refrains from relying on simulating the soil water balance. Frost damage effects presented with model outputs were simulated with the assumption of available frost protection, and after determining the frost effect factor, it was applied only to the current year and had no carry-over effect representing long-term damage to the productivity of the orchard. Hence, each season was independent of any damage that may have occured in the season preceeding it.

Simplifications applied in the presented approach are not necessarily associated with more advanced modeling techniques. Though even in current generation ecophysiological models the level of process detail ranges from simple approaches involving daily net productivity estimation, to models simulating the diurnal variation in leaf-level photosynthesis, or complex models calculating the soil-plant-atmosphere energy balance with sub-hourly time steps. Determining the appropriate scale and level of abstraction includes positions stating that due to uncertainties in parametrisation and complexity in model structure, models should aim to achieve the highest reasonable simplicity. The main counter-argument suggests there is no logical basis for restricting complexity provided model parametrisation is well tested and documented (White et al., 2011).

Climate projections intend to provide a reasonable description of a future state of the atmosphere with respect to a range of climatological relationships and assumptions of radiative forcing. They represent an efficient method to explore possible future scenarios under specified emission pathway rather than a deterministic forecasting tool, as GCMs simulating the interactions between the atmosphere, land surface, oceans and sea ice all have related uncertainties. Considerable source of uncertainty in regional features of GCM projections is related to the low spatial resolutions that fail to represent specific regional land patterns such as mountains and lakes which are capable of influencing local climates (Tubiello et al., 2002). Modelling uncertainty results from incomplete understandning or representation of the complex climate system within a single model. Typically, model uncertainty provides the major source of variability in ensemble projections for multidecadal lead times, while time scales a few decades ahead are predominantlly influenced by internal variablity (Hawkins and Sutton, 2009; Hawkins and Sutton, 2011). For this reason, researchers use the outputs of multiple feasible future projections to increase the confidence in the identified signal. Since each model is associated with its own uncertainty, utilizing ensemble model runs tends to improve achieved accuracy (Murphy et al., 2018). Hence, any specific future climate scenario must be viewed as an instance of a physically plausible representation of projected climate change.

Chapter 5

Conclusions

This study analyzed and discussed projected impacts of climate change on regional climate suitability for citrus production. Developed approach allowed for a clear conceptualization of key interactions and processes affecting fruit growth, and consequently related simulated projections to results obtained for a set baseline scenario. While made assumptions and simplifications limit the generalizability of model simulation results, identified trends and signals in future climate suitability are consistent with the consensus in cited literature.

This study demontrated how projected elevated heat stress represents a major constraining effect for future citrus production, affecting both areas with marginal and large-scale citriculture. The earliest and most susceptible stages of fruit growth, i.e. flowering and early fruit set periods, were most adversely affected. Furthermore, simulated rind colour development is projected to significantly decline across major citrus-producing regions with currently suitable conditions. Although frost related constraints are projected to decrease in a significant number of places, it cannot be concluded that citrus production simply shifting to such areas will be an effective response to projected climate change. Adaptation through appropriate management practices that will need to compensate for elevated environmental stress on the crop such as shading to mitigate temperature extremes, or degreening to address fruit marketability, seems feasible, however citrus cultivars with less stringent requirements can be expected to challenge economic suitability of more susceptible species. Adaptation of the trees or the anticipated CO_2 fertilisation effect still represent considerable influence on final suitability and would therefore allow for a more detailed assessment of the effects of climate change.

Development of a conceptual model offered specific advantages for a clear quantitative assessment of the effects of various environmental processes on crop phenology and fruit growth suitability, and synthesizes a variety of information into a single, self-contained package. This enables better understanding of the underlying effect of the environment on the crop. Furthermore, the architecture of the designed model allows for a straightforward modification of defined functional relationships. Ultimately, the approaches developed in this study provide potential for more involved and detailed investigations. Particularly relevant factor to consider in future research relates to appropriate conceptualisation of the effects of increased atmospheric CO_2 concentration, as the intensity of crop response will ultimately determine the future direction of trends in climate suitability.

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