Prospects of Cultivating Alternative Crops in a Changing Climate in Switzerland

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Abstract

Climate change today and in the future is changing the conditions for Swiss agriculture. Increasing temperatures and changing precipitation patterns hold opportunities but also increased risks. A qualitative and spatial shift in suitability is expected for major crops. The cultivation of alternative crops is hence a valuable adaption measure. This work aimed to identify alternative crops whose suitability will increase under projected climate changes and provide farmers with an initial indicator for planning. A simple model (ecocrop) was used to identify crops that will be adequately suited for future climate changes. The model was run with projected climate data for RCP4.5 and RCP8.5 for two future periods (2040-2070 and 2070-2100) for station Zurich. Only alternative crops were selected, and their nutritional quality was identified. Suitability maps for the reference period were created. Twenty-five different crops were selected, 20 crops under RCP4.5, and 22 crops under RCP8.5 (the results largely overlapped). The crops were described and discussed regarding their suitability at station Zurich, their spatial suitability and nutritional quality. The findings show that future climate changes will enable alternative crops to thrive in Switzerland. Under RCP8.5, the suitability for several crops decreased in the second future period, indicating that unabated climate change will ultimately have a negative impact, also on the crops discussed here. Nevertheless, growing alternative crops is an adaptation method and even a mitigation strategy, as, for example, emissions from imported crops could be avoided. Another opportunity arises from protein-rich legumes, which can be used as a substitute for meat and thus promote a plant-based diet that has been shown to cause fewer emissions. The lists and maps provided are an initial guide for farmers wishing to grow alternative crops and can help researchers decide which areas to focus on for further research. In future work, suitability maps need to be calculated for future periods to assess spatial shifts in suitability. Systematic field reports should be collected to include non-climatic factors in the evaluation of cropping potential.

Suggested Citation

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Abbreviations

RCM Regional Climate Model
GCM General Circulation Model
RCP Representative Concentration Pathway
UNFCCC United Nations Framework Convention on Climate Change
FAO Food and Agriculture Organization of the United Nations
IPCC Intergovernmental Panel on Climate Change
RDA Recommended Daily Allowance
EER Estimated Energy Requirement
INQ Index of Nutritional Quality
REF Reference period (1981-2010)
FUT1 First future period (2040-2070)
FUT2 Second future period (2070-2100)

1 Introduction

1.1 Relevance

Climate change is an indisputable reality in Switzerland. The consequences can already be seen and felt today and will increase in the future. From 1864 to 2017, an increase of about 2 °C was recorded, which is higher than the global average of 0.9 °C (National Centre for Climate Services NCCS, 2020). This development has already led to several changes in the Swiss climate, ecology, hydrology and agriculture. In addition to the average change in temperature and precipitation, extreme events' frequency and intensity also increase. Heatwaves and extreme precipitation occur more frequently today than in 1901 (CH2018, 2018). Droughts are becoming more frequent and are prolonged. The exceptionally dry summer of 2018 even led to regional restrictions limiting agricultural irrigation (Tratschin *et al.*, 2019). Such impacts of climate change are expected to increase in the future.

Depending on the Representative Concentration Pathway, Switzerland's mean temperature will rise by 2.1-3.4 °C (RCP2.6) or by up to 6.9 °C (RCP8.5) above the pre-industrial level. Combined with a decrease in summer precipitation, those changes will have a substantial impact on agriculture. Increasing water shortages and accelerated plant development in cereals and grain legumes are expected to result in yield losses (OcCC / ProClim, 2007). A spatial shift in suitability will occur for many crops. Without adaptations in varietal choices, yield declines are expected for winter wheat and in the long term also for grain maize in the central production regions in Switzerland (Holzkämper *et al.*, 2014). These developments call for adaptation measures for Swiss agriculture. Besides selecting better-adapted varieties to maintain common crops' productivity, crop choices also provide significant possibilities for adapting agricultural crop production to a changing climate. The identification of possible alternative crops is crucial to enable short and long-term planning for farmers.

1.2 Research objective

There is little information available on which alternative crops should be selected to expand the cultivation range. A crops' potential is a function of its climatic suitability, water use efficiency, nutrient content and economic perspective. Workload, acceptance and demand are crucial parameters for successfully introducing a crop to the market. Since not all factors can be considered in the scope of this work, the main focus will lie on climatic suitability.

The objective of this work is to investigate the prospects for growing alternative crops in a changing climate in Switzerland. The aim is to identify several crops that will benefit from the predicted climate changes in Switzerland and thus meaningfully complement the crop portfolio from a nutritional, agronomic and economic perspective.

1.3 Climate change in Switzerland

1.3.1 Reference climate

Switzerland is located in Central Europe and lies in the temperate climate zone. The climate is characterized by the influence of the westerlies and the Atlantic Ocean, which bring moist air via cyclones and fronts from the west. The Alps play a significant role in creating a spatially heterogenic climate (CH2018, 2018). When synoptic systems hit the Alps, they are often strongly modified. One well-known effect is the Föhn wind. The Alps create a climatic barrier between Northern and Southern Switzerland. Southern Switzerland is influenced by the Mediterranean Sea and characterized by a more mild climate, especially during winter (MeteoSchweiz, 2018a). Precipitation is highly influenced by topographic factors like orographic amplification or rain shadow effects. While an oceanic climate characterizes Western Switzerland, Eastern Switzerland's climate is more continental (Figure 1). Some regions, such as the Jura mountains, show minimal annual variability, whereas in most areas, there is a pronounced precipitation maximum in summer and a minimum in winter. In higher altitudes, a high amount of precipitation falls as snow. Most extreme precipitation events occur in the Ticino, while long-lasting, heavy precipitation is typical in the Jura mountains and the northern Alpine rim (CH2018, 2018). The Alps' inner valleys are relatively dry, as precipitation is blocked from both sides (see Sion in Figure 1). Corresponding to the large differences in altitude, the temperature range is also wide. In January, mean monthly temperatures (for a reference period from 1981-2010) range from 0°C to -15 °C and in July from 0 °C to 24 °C (MeteoSchweiz, 2018b). The highest mean monthly temperatures in January and July are obtained in Southern Switzerland. The lowest monthly mean temperatures in January and July occur in the Valais and Engadin (MeteoSchweiz, 2018b).

1.3.2 Current trends

CH2018 (2018) reports an increase in heatwaves, decreased Alpine glacier volume and a prolongation of the vegetation period. Heatwaves are 200%, and extreme precipitation

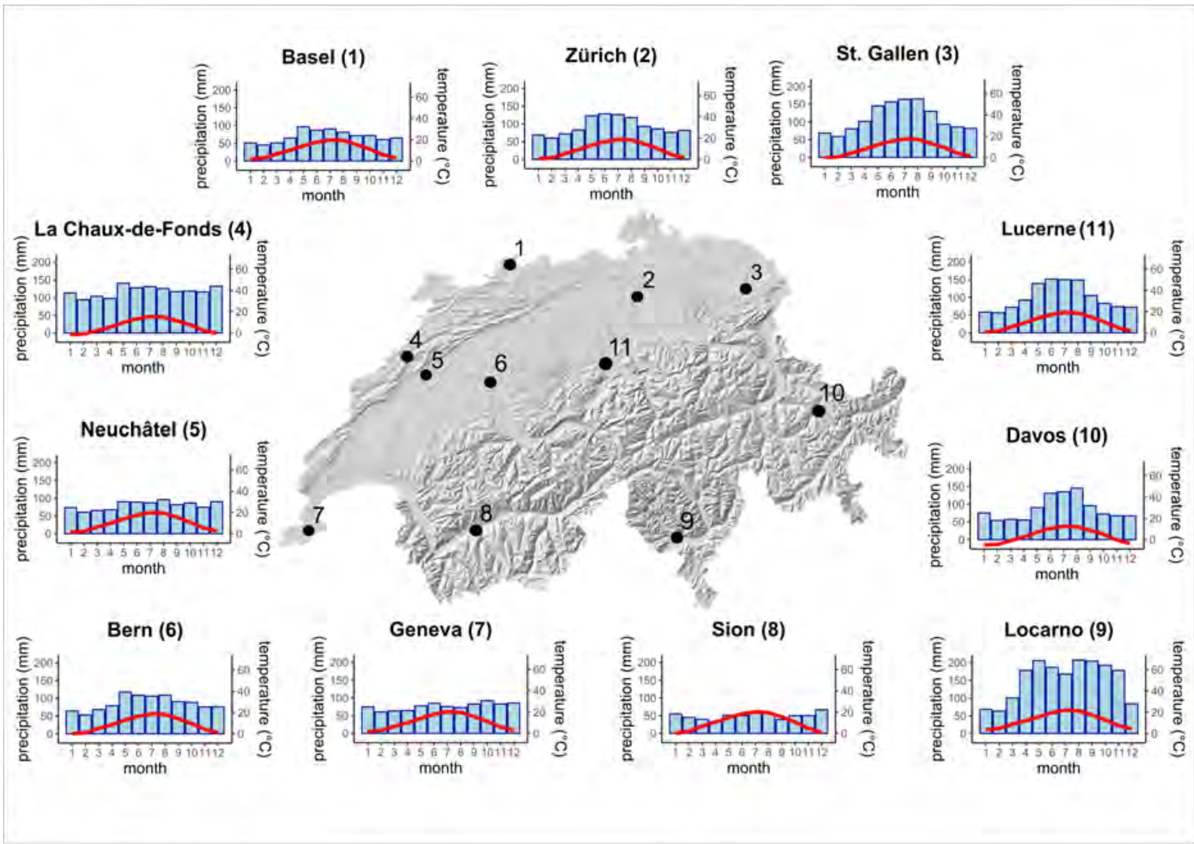

Figure 1: Monthly mean precipitation 1980-2019 and monthly mean temperatures 1980-2019. The selected weather stations underline the heterogeneity of the Swiss climate.

30% more frequent today than in 1901. Winter precipitation increased by 20-30% since 1864. Frost days (in low altitudes) are up to 60% and snow days 50% less frequent today than in 1961, respectively 1970. The volume of Alpine glaciers has decreased by 60% since 1864, as illustrated by the retreat of the Rhône glacier in Figure 2. The vegetation period has increased by 2-4 weeks since 1961 (National Centre for Climate Services NCCS, 2020). The exceptional dry summer and fall of 2018 even led to regional restrictions on withdrawals for agricultural irrigation (Tratschin *et al.*, 2019) (Figure 2).

1.3.3 Future trends

The Swiss Climate Scenarios (CH2018) were developed for different Representative Concentration Pathways (RCP) to assess future changes in the climate system and its impacts. The RCP scenarios were defined by the last IPCC Assessment Report (AR5) and describe how much radiative forcing is added by anthropogenic activity until 2100 relative to pre-industrial conditions (1750). They are explained in detail in Chapter 2.2.1. RCP8.5,

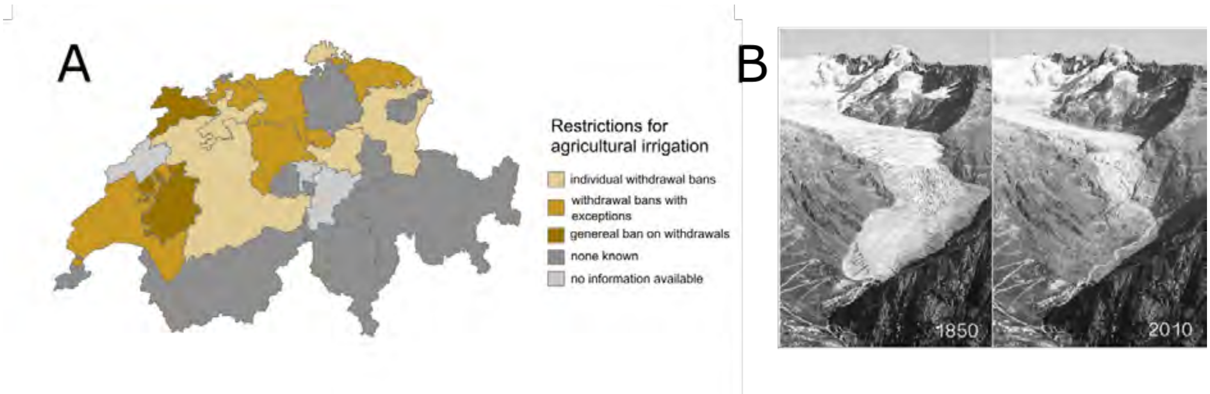

Figure 2: A: Restriction on irrigation withdrawals in 2018 (Tratschin *et al.*, 2019). B: retreat of the Rhône glacier from 1850 to 2010 (Mattavelli, 2016)

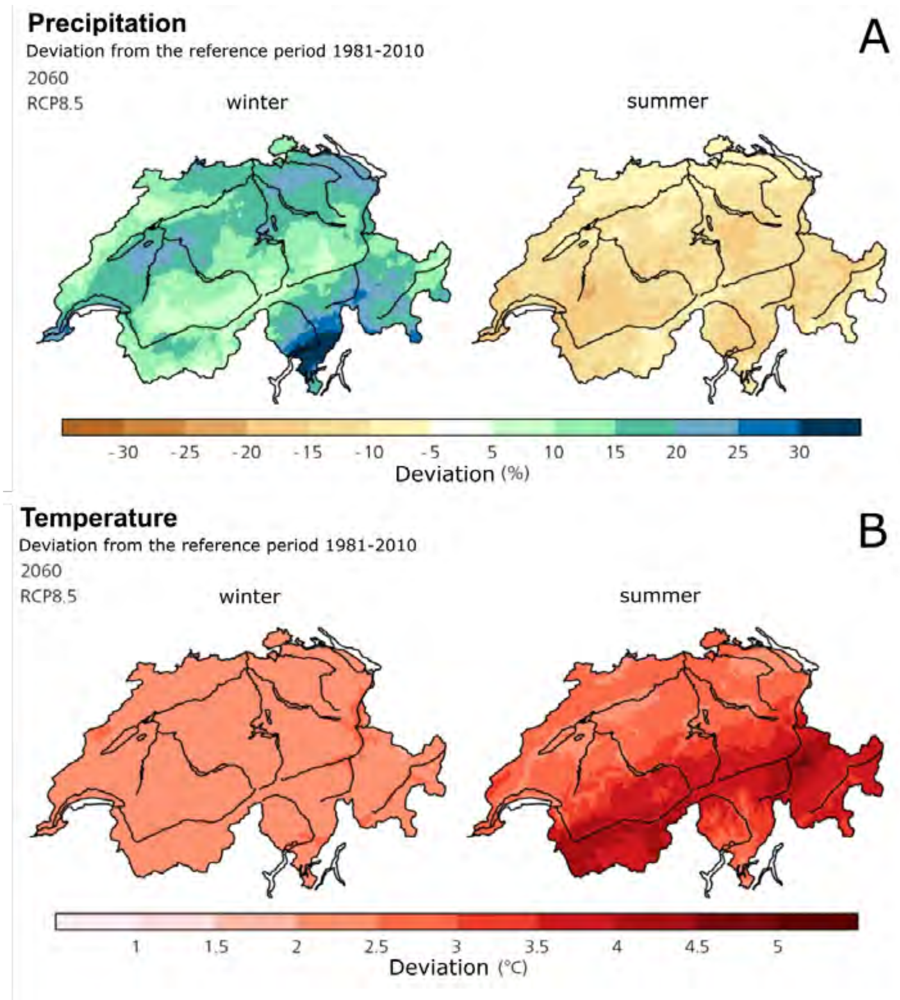

Figure 3: A: Precipitation in 2060 under RCP8.5 (deviation from reference period 1981-2010). B: Temperature in 2060 under RCP8.5 (deviation from reference period 1981-2010) (National Centre for Climate Services NCCS, 2019).

for instance, is a worst-case scenario with no abatement in greenhouse gas emissions and continued increase after 2100 (Benestad *et al.*, 2017). If the international community were to comply with the 2°C target (following the mitigation scenario RCP2.6), temperatures in Switzerland would likely increase by 2.1-3.4 °C above the pre-industrial level. If no mitigation measures are taken (RCP8.5), the annual mean temperature in Switzerland could be up to 6.9 °C above pre-industrial levels (CH2018, 2018). The increase would be more pronounced in the summer month, especially in the Alpine region (National Centre for Climate Services NCCS, 2019). Under scenario 8.5, average precipitation in Switzerland will decrease in summer by up to -39% and increase in colder seasons by up to 24% until the end of the century (Figure 3). While the reduction in summer precipitation is spatially homogeneous, the increase in winter is most pronounced south of the Alps and on the Central Plateau. According to the CH2018 (2018), snowfall and snow cover at lower altitudes will decrease significantly. All scenarios project the number of frost days to decrease. According to CH2018 (2018, p.111), at least 25 days/year will occur at lower elevations under RCP4.5, while only "very few" frost days are projected under RCP8.5.

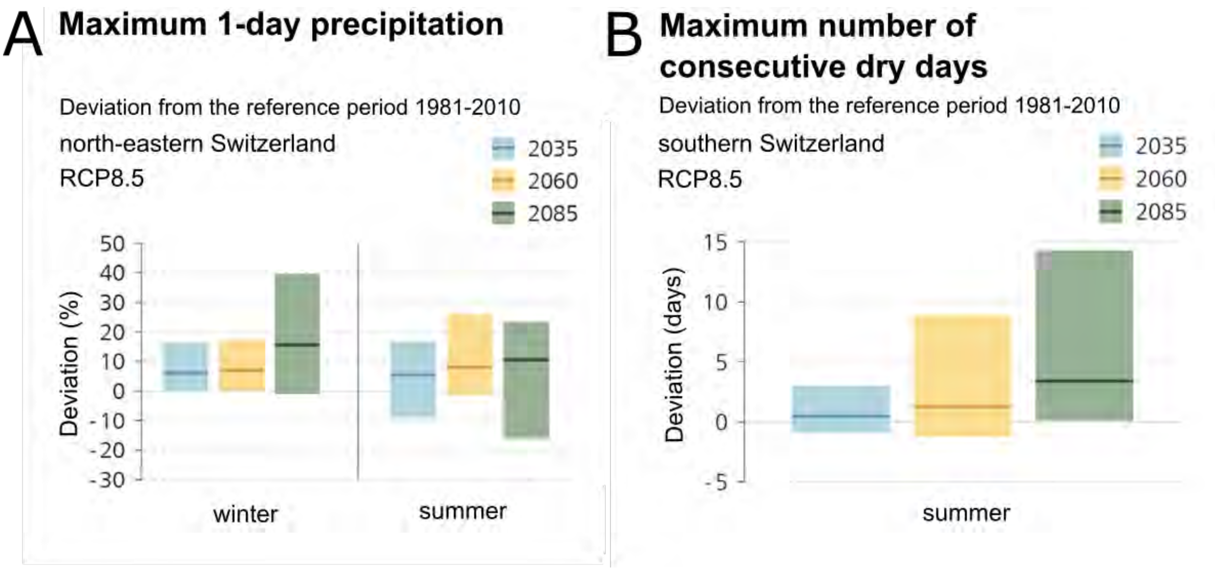

Figure 4: A: Maximum 1-day precipitation under RCP8.5 (deviation from reference period 1981-2010). B: Maximum number of consecutive dry days under RCP8.5 (deviation from reference period 1981-2010) (National Centre for Climate Services NCCS, 2019).

The frequency, intensity and duration of many climate extremes are likely to increase under unrestrained amplified emissions. Heatwaves will increase and play their part in amplifying evaporation. The duration and intensity of extremely dry periods in summer will increase (Figure 4). Due to higher temperatures, runoff from snowmelt will occur earlier, and therefore less water will be available in late summer. These effects will culminate in extremely dry soils. Extreme precipitation will increase following the Clausius-Clapeyron equation. The equation states that with increasing temperatures, saturation vapour pressure increases as well, and so does the atmosphere's moisture content. If the air warms by 1 °C, it can hold 6% more water. Simply put: extreme precipitation will not only occur more frequently but also more intensively (Figure 4). As the zero degree limit moves upwards, less precipitation will fall as snow but as rain, leading to more flooding (National Centre for Climate Services NCCS, 2019).

1.4 Impact on Agriculture

1.4.1 Global and regional scale

Agriculture is directly exposed to climate and hence very sensitive to climatic changes and climate variability. As expected, climate change does already have different impacts across Europe. According to the European Environment Agency (2019) and Kuebler (2020), crop productivity and relative profitability of agriculture in Southern Europe will decrease due to increasing temperatures, droughts, and new diseases. Olives, an important staple in Italy, are increasingly threatened due to the olive fruit fly, which benefits from warming winters (Kuebler, 2020). Farmers in southern Italy are even shifting their production from olives to tropical fruits like mango and papaya (Kuebler, 2020). Northern Europe, on the other hand, might experience benefits like a longer growing season and increasing suitability for a range of crops (European Environment Agency, 2019 and Kuebler, 2020). However, the increasing number and intensity of extreme events, late frosts or droughts have a negative impact on agriculture in Northern Europe as well. In 2020, German farmers experienced the third consecutive year of substantial yield loss due to insufficient rainfall (Kuebler, 2020). Mabhaudhi *et al.* (2019), Pugh *et al.* (2016) and Gardner *et al.* (2021) expect climate change to cause a significant reduction in yields of global staple crops like wheat, maize and rice by 2050. According to Pugh *et al.* (2016), wheat yields in Central Europe will decrease by 20% by mid-century and by 40% until the end of the century. Maize will not experience a substantial change first, but the yield will decrease by the end of the century by approximately 20% (Pugh *et al.*, 2016). The potential to increase crop yield by intensification on current croplands is limited. In fact, yields on current farmland will decline worldwide. However, the potential of hitherto uncultivated land is increasing at higher latitudes (Pugh *et al.*, 2016).

1.4.2 National and local scale

If warming is below 2-3 °C, the overall impact on Swiss agriculture is expected to be relatively positive (OcCC / ProClim, 2007). This assumption is very general, and the nature of the effects varies according to region, plant species and variety. If sufficient water and nutrients are available, the yield for cereal crops and pasture could increase due to the extension of the vegetation period (CH2014-Impacts, 2014). However, an increase in evapotranspiration of plants and soil with a simultaneous decrease in summer precipitation will lead to a water supply shortage. In 2018, this scenario already occurred, when water withdrawal for agriculture was locally restricted due to severe drought (Chapter 1.3.2). If warming exceeds 2-3 °C by 2050, the adverse effects will outweigh the positive effects. Increasing water shortages and accelerated plant development in cereals and grain legumes will lead to yield losses (OcCC / ProClim, 2007). In Western and North-eastern Switzerland, warming would enable the cultivation of grape varieties that rely on higher temperatures, allowing viticulture to benefit initially. Spatial shifts of suitable zones for cultivation are expected for a whole range of especially warm-season crops (Holzkämper *et al.*, 2013; Girvetz *et al.*, 2019).

Continued warming, however, would have negative consequences, as for some crops, temperature thresholds would be exceeded (CH2014-Impacts, 2014). Temperature extremes cause significant damage, especially when they coincide with critical developmental stages (Holzkämper *et al.*, 2013). Holzkämper *et al.* (2014) model current and discuss future suitability of two major crops in Switzerland, maize and winter wheat. Maize is initially expected to benefit from recent warming of 0.5 °C/decade and will later be constrained by water scarcity in summer as a result of progressive warming. The suitability of winter wheat already decreased from 1983 to 2010, which is likely due to heat stress. These trends will be more pronounced with future climate change. Another negative side effect of higher temperatures is that pests can develop more than one or even two generations per year, causing increased damage to agricultural products. A prominent example is the codling moth, a major pest insect in apple orchards. In Southern Switzerland, a third generation per year will probably already occur by the middle of the century.

1.5 Adaptation to climate change

To cope with shifts in temperature and precipitation, farmers should consider alternative crops that are better adapted to future climatic conditions (OcCC / ProClim, 2007). As aforementioned, it can be an opportunity to grow other crops or varieties of crops that are rarely or not grown under current conditions. Crops like quinoa or chick pea that were not well known in Switzerland just a few years ago are now produced in Switzerland and are successfully entering the market. The market for protein-rich legumes that can be used as meat substitutes for a vegetarian diet is growing (Asgar *et al.*, 2010). A further incentive for growing alternative crops for farmers is that diversity in crop rotation can increase soil fertility. Future changes in climatic conditions may spatially shift the suitability of crops. As an adaptation measure, land allocation for the production of certain crops and crop management should be adjusted. One could expect plants with a C4 metabolism, meaning they can fix carbon with a higher water use efficiency than crops with a C3 metabolism, to have an advantage in a hotter and drier climate. However, maize as a very productive C4 crop, for example, will be less CO_2-limited. Therefore, water limitations will also play a more significant role for this crop in the future (van Zonneveld *et al.*, 2020). Wheat as a C3 crop is less tolerant to water and heat stress, which is mirrored by the findings of Holzkämper *et al.* (2014). If the best-suited crops are identified and cultivated, OcCC / ProClim (2007) expect that Swiss agriculture could adapt to a warming of 2-3 °C until 2050. Another reason to focus on C4 crops is presented by Myers *et al.* (2014), which looked at the effects of elevated CO_2 on human nutrition. They found that growing under elevated atmospheric CO_2, the nutritional value of C3 plants is lowered while C4 plants seem to be less affected (Myers *et al.*, 2014).

1.6 Potential benefits of alternative crops

While the potential for intensification on current cropland might be limited, the warming climate might enable novel crops to be cultivated, such as in Central and Northern Europe (European Environment Agency, 2019 and Gardner *et al.*, 2021). The cultivation of alternative crops is hence seen as a useful adaptation, but also as a mitigation measure to climate change (European Environment Agency, 2019 and Gardner *et al.*, 2021). According to Gardner *et al.* (2021), growing alternative crops could reduce emissions that would otherwise be generated by importing those crops. A commonly used tool to determine climate change impacts on a crop and to assess regional crop-suitability shifts is the simple mechanistic model ecocrop (Ramirez-Villegas *et al.*, 2013, Abdallah and Jaafar, 2019 and Makinano-Santillan and Santillan, 2015).

The agricultural sector in Switzerland is changing as the number of small businesses and people working in this sector is declining (Schwab, 2017). While the total number of farms is regressive, organic farms are on the rise, making 13.4% of the total Swiss agricultural area in 2017 (Schwab, 2017). There is a trend towards organic and regional produced food. This is indicated by major retailers like Coop and Migros creating labels like Naturaplan, Oecoplan, Pro Species Rara and Miini Region. According to Schwab (2017), niche products and alternative crops are mostly cultivated on small farms and on a small scale. To be competitive with imports, farmers must produce ecologically and sustainably to justify the higher price level (Heine *et al.*, 2018). Besides that, important prerequisites to grow alternative crops are the willingness to take risks, interest and know-how (Schwab, 2017).

Heine *et al.* (2018) see the rising demand for plant-based products and especially proteins as a chance for Swiss agriculture. Instead of importing unsustainably produced soybean from which 68% of global meat substitutes in 2016 were made, soybean or other legumes could be regionally produced. Protein crops that could be cultivated in Switzerland are, for example, lupine (white and blue), common bean and scarlet runner bean (Heine *et al.*, 2018). From a nutritional perspective, they are good sources of protein, carbohydrates, and some amino acids. In some cases, the legumes are very well comparable or even better than beef regarding their nutritional quality (Heine *et al.*, 2018).

The cultivation of almond trees instead of cherry trees represents an opportunity, as cherry orchards are becoming less profitable and more challenging due to consumers' high expectations and pest infestation (Reutimann *et al.*, 2020). The findings of Reutimann *et al.* (2020) suggest sufficient demand and that cultivation is possible in regions where grapes and apricots are grown today. Limitations are seen in competing with low prices of imported almonds with a comparable or even better quality. Nevertheless, Reutimann *et al.* (2020) see the potential in labelling it as a regional product "Swiss almond" and thus finding sufficient customers.

1.7 Outline

This work's approach is to start with a broad range of crops and analyse their potential to contribute to sustainable and diversified Swiss agriculture under climate change conditions in the future. Therefore a simple model will be used to determine the crop's climatic suitability. After the crops with the highest values are selected, their nutritional value is determined. For each category: cereals, fruits and nuts, legumes, oilseeds, tubers and vegetables, at least one alternative crop is represented. Maps of climatic suitability in the reference period are produced for all crops to obtain a spatial assessment in addition to the station-based modelling.

2 Methods

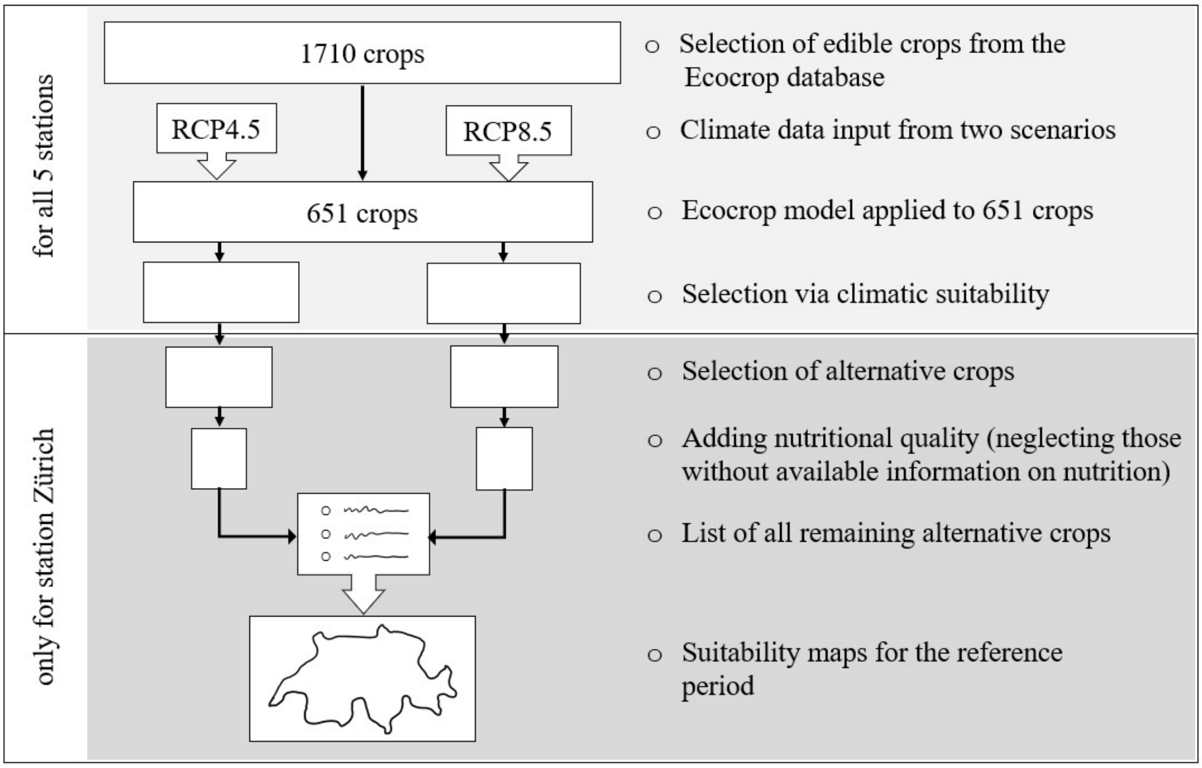

Figure 5: Methodological proceeding and selection scheme for alternative crops.

2.1 Categorisation

As a first step, all crops in the Ecocrop database were categorised following the FAO crop classification standards (World Program for the Census of Agriculture, 2010) (Appendix A.1). An overview of this and the following steps can be seen in Figure 5. The Ecocrop database is included in the simple mechanistic model ecocrop of the R package dismo Hijmans (2020). The database contains 1710 crops which are defined by 35 parameters. Since this work focuses on food crops, only edible crops were selected, leaving 651 crops.

2.2 Climate data input

The bias-corrected CH2018 projection data was used as climate data input for the model. The data is available for 58 stations in Switzerland in daily resolution from 1981 until 2099. The gridded data was statistically downscaled to a spatial resolution of 2 km x 2 km. A set of parameters is given, ranging from daily temperature means and precipitation to relative humidity. The CH2018 scenarios were derived from an ensemble of Regional Climate

Models (RCM), provided by the European Coordinated Downscaling Experiment (EURO-CORDEX). The RCM translate the much coarser General Circulation Models (GCM) to a level that adequately represents the main topographic properties of Switzerland (CH2018, 2018). The combination of a GCM and an RCM is called a model chain. The ecocrop model requires climate data input in the form of a vector containing monthly mean values of daily minimum temperature, daily average temperature, and monthly precipitation sums. Three Representative Concentration Pathways (RCP) based on the latest generation of climate models are provided for Switzerland (CH2018, 2018).

2.2.1 Representative Concentration Pathways (RCP)

The RCP scenarios were defined by the last IPCC Assessment Report (AR5) and describe how much radiative forcing is added by anthropogenic activity by 2100 compared to 1750. It is important to stress that the RCP senarios are projections and not predictions due to the limited understanding of natural climate variability and the uncertainty of climate extremes, political decisions and socio-economic factors (CH2018, 2018). The scenarios cover emissions and concentrations of the full spectrum of greenhouse gases and aerosols. Land use and land cover are also included. The paths represent only one possible scenario out of many combinations of properties that lead to a change in radiative forcing. Defining and communicating the RCP scenarios is very important, as they represent the severe consequences of our actions and show the possibilities that can be achieved with mitigation strategies. Following the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC), the Conference of the Parties (COP) agreed to keep mean global warming until 2100 well below 2 °C above preindustrial levels (United Nations Framework Convention on Climate Change, 2016). RCP2.6 refers to a path that will lead to an additional 2.6 W/m^2 by 2100 (Figure 6). The paths will peak before the end of the century and then decline. This scenario would go hand in hand with a 2 °C compliant mitigation of emissions and meet the Paris agreement's objectives since the global mean temperature would increase by less than 2 °C. RCP4.5 describes a path that will peak after 2100 and lead to an additional 4.5 W/m^2. This level of radiative forcing will increase the global mean temperature by more than 2.5 °C. RCP8.5 is the most extreme scenario, projecting an increasing radiative forcing of 8.5 W/m^2 by 2100 and even an increase after that (van Vuuren *et al.*, 2011). In this scenario, unabated emissions will increase the global mean temperature by 4-5 °C. Some of the global warming effects will have a more substantial, more severe and faster regional impact. Warming in Switzerland under the RCP2.6 scenario will likely be in a range of 2.1-3.4 °C. Unmitigated warming under RCP8.5 might lead to an increase in the annual mean temperature of up to 6.9 °C

(CH2018, 2018). Modelling and analysis in this work will be based on RCP4.5 and RCP8.5 as fewer simulations were available for RCP2.6 and none for RCP6.0. Also, RCP2.6 does not seem very realistic five years after the Paris Agreement. According to an analysis by Watson *et al.* (2019) 75% of the 184 individual objectives to reduce the emissions by 2030 are partially or entirely insufficient.

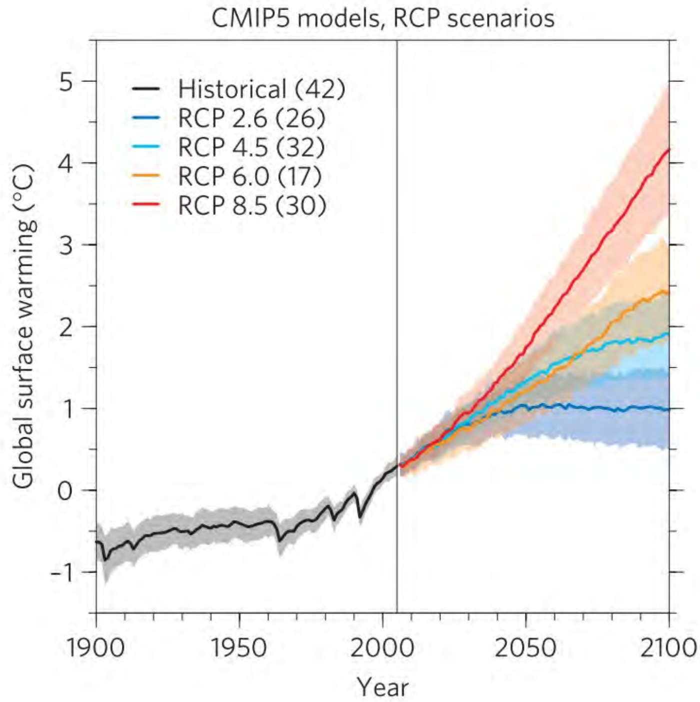

Figure 6: Global mean surface temperature change in response to different RCP scenarios. Number of models is given in the brackets. Standard deviation shown as shading (Knutti and Sedláček, 2013).

2.2.2 Model chains

The EUR-11 ensemble was chosen, which contains a simulation in a horizontal resolution of 12 km. The quality of the individual chains depends mainly on the GCM on which they are based. Since there are different numbers of RCM per GCM, an ensemble mean and range might not reflect the real model uncertainty (CH2018, 2018). Considering this condition, an ensemble mean is nevertheless calculated for the model parameters' monthly mean values. Even if the range does not reflect the total uncertainty, the mean should compensate for extreme values. The ten different model chains chosen for this analysis can be seen in Table 1.

Table 1: 10 different model chains used in the ecocrop model calculation. GCM= General Circulation Model. RCM= Regional Climate Model. RCP= Representative Concentration Pathway.

GCM	**RCM**	**RCP**
ECEARTH_EUR11	CLMCOM-CCLM4	4.5
		8.5
	SMHI-RCA	4.5
		8.5
	DMI-HIRHAM	4.5
		8.5
MPIESM_EUR11	CLMCOM-CCLM4	4.5
		8.5
	MPICSC-REM01	4.5
		8.5
	MPICSC-REM02	4.5
		8.5
	SMHI-RCA	4.5
		8.5
HADGEM_EUR11	CLMCOM-CCLM4	4.5
		8.5
	SMHI-RCA	4.5
		8.5
IPSL_EUR11	SMHI-RCA	4.5
		8.5

2.3 Ecocrop model

The ecocrop function of the dismo package (v.1.1-4) by Robert J. Hijmans is used in R (1.2.5042). It is based on the same-named databank developed by the Food and Agriculture Organization of the United Nations (FAO). The 651 edible crops that were obtained in Chapter 2.1 will be fed into the model. The ecocrop function can assess the regional suitability of crops for a certain environment and give a first approximation of climate change impacts on the crop's suitability (Manners and van Etten, 2018 and Gardner *et al.*, 2021). Ecocrop simulates to what extent each month's climatic conditions fall within crop-specific thresholds of temperature and precipitation (Figure 7). Each crop inside the database is defined by ranges for the two parameters temperature and precipitation (Ramirez-Villegas *et al.*, 2013). The absolute boundaries are defined by T_{MIN}/T_{MAX}, respectively R_{MIN}/R_{MAX}. The optimum range is defined by T_{OPMIN}/T_{OPMAX}, respectively R_{OPMIN}/R_{OPMAX} (Figure 7).

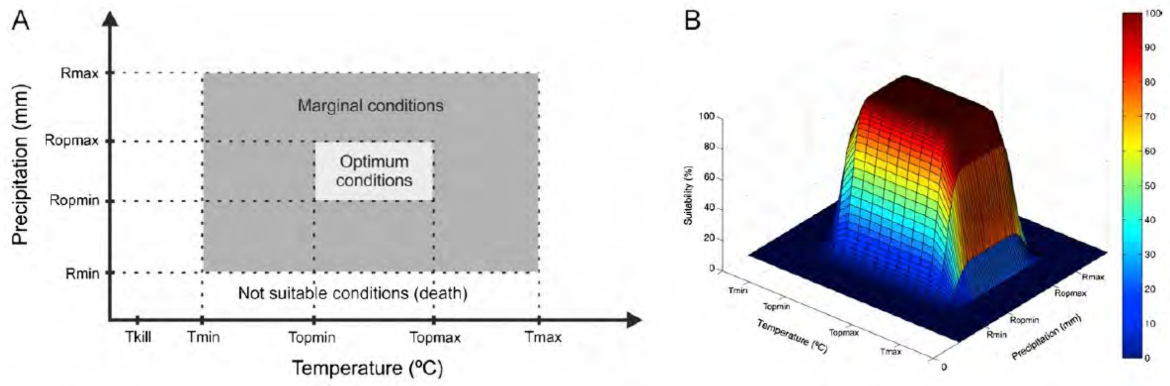

Figure 7: Crop suitability as a function of temperature and precipitation. The ecocrop model in (A) two-dimensional and (B) three-dimensional form (Ramirez-Villegas *et al.*, 2013).

To include the possibility that the actual temperatures during a month exceed a crop's absolute threshold, the parameter T_{kill} is added. If the mean minimum temperature of a place is below T_{kill} + 4 °C, the model assumes that the T_{kill} temperature will be reached during this month. In this case, the crop would not survive, and its suitability for this place would be 0. If the outer limits of the requirements are exceeded, a suitability value of 0 will be returned. If the maximum and minimum requirements are met, a value between 0 and 1 will be returned. If the local climatic parameters are within the optimal conditions, a suitability value of 1 is fulfilled. A description of the suitability values is given in Table 2.

Table 2: Key for the suitability values, taken from Egbebiyi *et al.* (2020).

Index value	Description
0-0.2	Unsuitable
0.2-0.4	Very marginally suitable
0.4-0.6	Marginally suitable
0.6-0.8	Suitable
0.8-1	Highly suitable

Another important parameter is the crop's specific length of the growing season. For site (P), for each month (i) of the growing season and for each of the 12 potential growing seasons of the year (assuming that each month is potentially the first month of the growing season), the suitability (T_{SUIT} or R_{SUIT}) is calculated. The calculation is done by comparing the various plant parameters with the climate data that is fed into the model (Equation 1 and 2). According to Ramirez-Villegas *et al.* (2013, p.68) "where a_{T1} is the intercept and m_{T1} the slope of the regression curve between $T_{MIN\text{-}C,\,0}$ and $T_{OPMIN\text{-}C,\,100}$; and a_{T2} is the intercept and m_{T2} the slope of the regression curve between $T_{OPMAX\text{-}C,\,100}$ and $T_{MAX\text{-}C,\,0}$". "a_{R1} is the intercept and m_{R1} the slope of the regression curve between $R_{MIN\text{-}C,\,0}$ and $R_{OPMIN\text{-}C,\,100}$; and a_{R2} is the intercept and m_{R2} the slope of the regression curve between $R_{OPMAX\text{-}C,\,100}$ and $R_{MAX\text{-}C,\,0}$", according to Ramirez-Villegas *et al.* (2013, p.68). The model output for R_{SUIT} is calculated with $R_{TOTAL\text{-}P}$, the precipitation sum of all growing season's month. Suitability is calculated as the product of the temperature (T_{SUITi}) and rainfall suitability (R_{SUIT}) (Equation 3). The model output for SUIT are monthly suitability values for each crop (C) between 0 (unsuitable) and 1 (highly suitable).

$$T_{SUITi} = \begin{cases} 0 & T_{MIN-Pi} < T_{KILL-M} \\ 0 & T_{MEAN-Pi} < T_{MIN-C} \\ a_{T1} + m_{T1} * T_{MEAN-Pi} & T_{MIN-C} \leq T_{MEAN-Pi} < T_{OPMIN-C} \\ 100 & T_{OPMIN-C} \leq T_{MEAN-Pi} < T_{OPMAX-C} \\ a_{T2} + m_{T2} * T_{MEAN-Pi} & T_{OPMAX-C} \leq T_{MEAN-Pi} < T_{MAX-C} \\ 0 & T_{MEAN-Pi} \geq T_{MAX-C} \end{cases} \tag{1}$$

$$R_{SUIT} = \begin{cases} 0 & R_{TOTAL-P} < R_{MIN-C} \\ a_{R1} + m_{R1} * R_{TOTAL-P} & R_{MIN-C} \leq R_{TOTAL-P} < R_{OPMIN-C} \\ 100 & R_{OPMIN-C} \leq R_{TOTAL-P} < R_{OPMAX-C} \\ a_{R2} + m_{R2} * R_{TOTAL-P} & R_{OPMAX-C} \leq R_{TOTAL-P} < R_{MAX-C} \\ 0 & R_{TOTAL-P} \geq R_{MAX-C} \end{cases} \tag{2}$$

$$SUIT = R_{SUIT} * T_{SUIT} \tag{3}$$

The model is calculated for a reference period (1981-2010) and two future periods (2040-2070 and 2070-2100) for RCP4.5 and RCP8.5. In this way, the current and emerging suitability and thus the potential of a crop can be determined. The maximum suitability value is selected from the 12 suitability values for each month. It reflects the potential that a crop can reach, starting the growing season in the month where the value is met. Only the maximum suitability value is considered in the following. The model can be specified with the parameter "rainfed", set to TRUE or FALSE. If the parameter is set to FALSE, the model assumes the crop to be irrigated. The crop's precipitation requirements would then always be fulfilled. Since it is more desirable to choose a crop that does not rely on irrigation to thrive, only the rainfed option will be considered in this analysis. The model will be computed over five stations in different environments to trace the model's sensibility and range. The stations used are Changins in southwestern Switzerland, Basel in the northwest, Zürich in Central Switzerland, Samedan in the east and Lugano south of the Alps (Figure 8). Basel, as well as the elevated Samedan, is relatively dry. Zürich, Changins and especially the warm tempered Lugano receive a relatively large amount of precipitation. Due to time limitations, further analysis (selection of crops that meet the criteria and mapping their suitability) is only conducted for station Zürich.

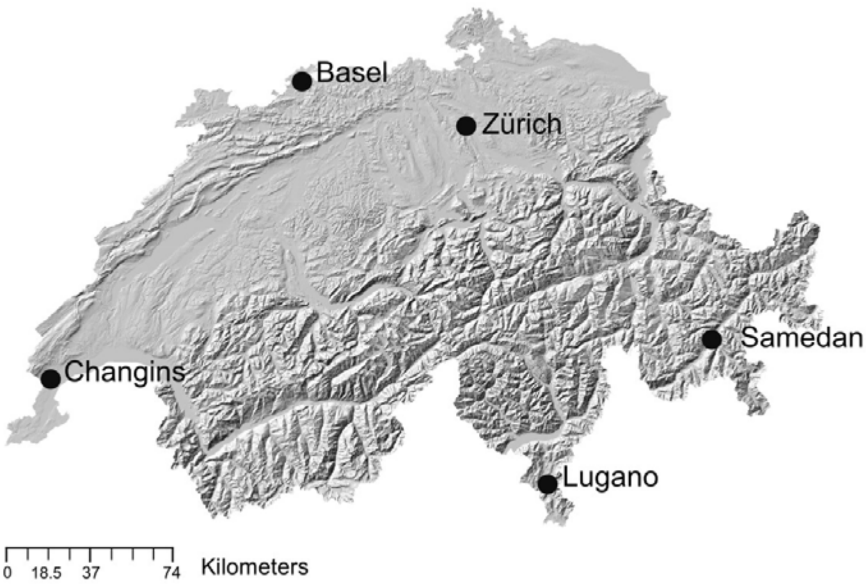

Figure 8: Location of the stations Zürich, Changins, Basel, Lugano and Samedan.

2.4 Selection via climatic suitability

According to their projected maximum suitability (max_suit), a subsection of crops is made using the following criteria:

1. max_suit FUT1 > 0.6 **OR** max_suit FUT2 > 0.6
   AND
2. max_suit FUT1 > max_suit REF **OR** max_suit FUT2 > max_suit REF

REF is the reference period 1981-2010, FUT1 is the first future period 2040-2070 and FUT2 the second future period 2070-2100. This step in the selection process was conducted for all stations. The following steps are only conducted for station Zürich. The climatically suitable crops are selected according to whether they are alternative or not. Research was therefore carried out to determine whether a crop was already being cultivated on a large scale in Switzerland, and if this was the case, it was excluded from further analysis. Climatic suitability is not the only aspect determining a crop's potential to be grown, sold and consumed. Hence another measure of potential was applied.

2.5 Nutritional quality

To further evaluate the remaining crops, their nutritional value was determined by calculating the Index of Nutritional Quality (INQ). Several databases, namely the Swiss food composition database, the USDA food central, the FAO/INFOODS Food composition table for West Africa (2019), and the FAO/INFOODS Global food composition database for pulses – version 1.0, were used to research the nutritional content of each crop. There was no, or only little information available for several crops, since they are under-researched or hardly known. The crops will be analyzed regarding the recommended daily intake of 24 essential vitamins, minerals and other nutrients defined by the Schweizerische Gesellschaft für Ernährung (2015). The INQ is used to compare the nutrient content with the Recommended Daily Allowance (RDA) of a crop. If the INQ is larger than 1, a crop can be labelled as a good source of that specific nutrient. A reference value for the nutrient must be calculated using the mean estimated energy requirement (EER) to compute the INQ. According to the National Research Council (1989), the daily mean EER for women is 2200 kcal. It should be considered that women need lower amounts of all nutrients than man, except for iron. The RDA values can be found in Appendix A.4.

$$\text{Index of nutritional quality} = \frac{\text{Nutrient content (per 1000 kcal)}}{\text{RDA (per 1000 kcal)}} \tag{4}$$

For several crops, there is no information on the nutritional composition available. Those crops are excluded from further analysis. The remaining crops are ranked inside their categories according to their climatic suitability and nutritional quality. At least one crop per category is presented as a potent alternative. While for some categories, only one crop has potential at all, there is more than one promising crop for other categories. The results will include two lists, one for each scenario. The individual crops on those lists will be characterized by the parameters climatic suitability and nutritional quality.

2.6 Mapping

In order to make a statement about the spatial manifestation of climatic suitability, maps are produced for all selected crops. For this purpose, the climatic suitability of a crop is calculated for each grid cell (2 km x 2 km). The model is calculated using the historical spatial climate data from MeteoSwiss for the reference period (1981-2010). Since the climatic suitability was up to this point calculated on a station basis under two different scenarios, the reference values were also calculated with the climate data projected for the respective scenario. Slight differences between the station-based projected data and the grid-based historical data are to be expected as they represent the model chain bias of the two scenarios with respect to the historical data. The resulting 241 x 203 matrix was exported from R and imported into ArcGIS (v10.60). There it was converted into a raster file and further transformed into a map with spatial reference.

2.7 Model chain bias

In addition to the suitability maps, the model was applied using the station-based historical climate data from MeteoSwiss. This way, the station-based suitability values derived from the projected climate data were compared to station-based suitability values derived from the historical climate data from MeteoSwiss. Apart from showing the bias, the comparison is valuable because the results from the historical grid-based and station-based data could also differ.

3 Results

3.1 Selection process

According to the guidelines of the Food and Agriculture Organization of the United Nations (2010) (Appendix A.1), all crops were classified into one or more categories. 651 crops were labelled as "having potential", where potential is determined by whether a crop is edible or not. All 651 crops were fed into the ecocrop model, as were the climate data inputs for the different scenarios and periods. The result was one maximum suitability value for each crop per scenario, period and station. A filter was used to select crops following the criteria explained in Chapter 2.4. The model generated one list per scenario for each station, containing the crops that fulfilled the criteria. The number and composition of crops differed among the five stations Zürich, Changins, Samedan, Basel and Lugano (Figure 8). The results for all stations can be seen in Appendix A.2. It should be noted that those lists are not further reduced and therefore, not only alternative crops are included. The further selection process was only carried out for Zürich. An overview of the results for all stations, including the share of highly suitable crops per station, can be found in Appendix A.3. Lugano has the highest number of crops under scenarios 4.5 and 8.5 and the highest share of highly suitable crops with 74% and 62%, respectively. Zürich has 55 crops on the list under RCP4.5, where 36% are highly suitable. Under RCP8.5, more crops are listed (74), and the share of highly potential ones is higher (47%). In Changins, more crops are listed under RCP8.5 than under RCP4.5, and the share of highly potential crops is higher under RCP8.5. Basel counts more crops under RCP4.5, but the share of highly potential crops is larger under RCP8.5. In Samedan, there are only two crops on the list for both scenarios, one of which is highly suitable in each case. In Zürich and Changins, more crops meet the criteria under RCP8.5, whereby the proportion of very suitable crops is also higher. In Basel, more crops meet the criteria under RCP4.5, and in Samedan and Lugano, the same number of crops is achieved under both scenarios (Appendix A.2). Zürich was chosen as the station giving the selection of potentially suitable crops. Following the selection scheme (Figure 5), two lists for Zürich, one for each scenario containing 55 (RCP4.5) and 74 crops (RCP8.5), were further reduced. As some of the crops were already well-known and cultivated in Switzerland, they were omitted. The remaining 33, respectively 42, crops were analyzed from the nutritional viewpoint. The INQ could only be calculated for the crops for which information on the components was available and therefore, the lists were further reduced. The final lists included 20, respectively 21, crops. Most crops on the lists were identical so that, in total, 25 crops with high potential were identified. The results for these 25 crops are now presented considering the following bullet points:

1. Climatic suitability (station-based)

2. Model chain uncertainty

3. Climatic suitability (grid-based)

4. Nutritional quality

It should be noted that the amount of information available for some better-known crops differs from that for other crops, as they have not yet been sufficiently researched. The INQ should also be looked at critically since the reference portion of 100 g is not necessarily a realistic portion consumed in one day for some crops like herbs and nuts.

Table 3: Potential crops for Zürich under RCP4.5. REF= reference period (1981-2010), FUT1= first future period (2040-2070), FUT2= second future period (2070-2100). SD= standard deviation from the multi-model mean. INQ count = number of nutrients for which the crop counts as a good source. Info. avail.= indicates for what percentage of the 24 nutrients listed in the Appendix A.4 information is available.

Type	Crop	Scientific name	REF		SD	FUT1		SD	FUT2		SD	INQ count	Info. avail. (%)
Beverage/ spice crops	Black mustard	Cullenia rosayroana Koster.	0.85	±	0.06	0.94	±	0.1	0.98	±	0.04	3	29
	Wormseed	Chenopodium ambrosioides L.	0.50	±	0.03	0.64	±	0.04	0.68	±	0.03	14	75
	Borage	Coleus amboinicus Lour.	0.50	±	0.03	0.61	±	0.05	0.67	±	0.05	14	71
	Hot pepper	Capsicum frutescens	0.56	±	0.03	0.64	±	0.06	0.70	±	0.04	7	46
Cereals	Browntop millet	Brachiaria ramosa (L.)Stapf	0.69	±	0.03	0.76	±	0.22	0.91	±	0.13	5	46
	Quinoa	Chenopodium quinoa Willden.	0.63	±	0.03	0.74	±	0.03	0.77	±	0.03	3	100
	Wheat, durum	Triticum durum Desf.	0.65	±	0.03	0.72	±	0.12	0.76	±	0.09	11	100
	Teff	Eragrostis tef (Zucc.) Trot	0.62	±	0.01	0.64	±	0.08	0.69	±	0.05	9	67
Fruits and nuts	Cranberry	Vaccinium macrocarpon Ait.	0.73	±	0.02	0.76	±	0.11	0.87	±	0.06	10	100
	Black walnut	Juglans nigra L.	0.60	±	0.02	0.69	±	0.08	0.72	±	0.04	3	50
	Sesame seed	Sesamum indicum L.	0.45	±	0.02	0.61	±	0.05	0.69	±	0.06	10	100
	Pecan nut	Carya illinoensis Wangenh.	0.44	±	0.03	0.61	±	0.06	0.65	±	0.05	4	46
	Almond	Prunus amygdalus Batsch.	0.00	±	0.01	0.50	±	0.22	0.73	±	0.17	8	100
Legume	Lentil	Lens culinaris Medikus	0.81	±	0.03	0.86	±	0.07	0.94	±	0.05	10	100
	White Lupine	Lupinus albus L.	0.71	±	0.02	0.86	±	0.06	0.90	±	0.05	12	75
	Yellow Lupine	Lupinus luteus L.	0.60	±	0.03	0.69	±	0.04	0.72	±	0.04	10	71
	Scarlet runner bean	Phaseolus coccineus L.	0.00	±	0	0.52	±	0.36	0.74	±	0.27	1	16
Oilseeds	Sunflower	Helianthus annuus L v macro	0.68	±	0.02	0.71	±	0.12	0.74	±	0.08	1	29
Root/ tubers	Chufa	Cyperus esculentus L.	0.95	±	0.03	0.96	±	0.11	0.98	±	0.04	6	50
Sugar crop	Sugar maple	Acer saccharum	0.52	±	0.02	0.62	±	0.12	0.73	±	0.05	1	54

Table 4: Potential crops for Zürich under RCP8.5. REF= reference period (1981-2010), FUT1= first future period (2040-2070), FUT2= second future period (2070-2100). SD= standard deviation from the multi model mean. INQ count = Number of nutrients for which the crop counts as a good source. Info. avail.= indicates for what percentage of the 24 nutrients listed in Appendix A.4 information is available.

Type	Crop	Scientific name	REF		SD	FUT1		SD	FUT2		SD	INQ count	Info. avail. (%)
Beverage/ spice crops	Black mustard	Cullenia rosayroana Koster.	0.85	±	0.06	0.98	±	0.03	0.94	±	0.13	3	29
	Wormseed	Chenopodium ambrosioides L.	0.50	±	0.03	0.70	±	0.04	0.73	±	0.08	14	75
	Borage	Coleus amboinicus Lour.	0.50	±	0.03	0.73	±	0.03	0.62	±	0.22	14	71
	Hot pepper	Capsicum frutescens L.	0.56	±	0.03	0.70	±	0.05	0.77	±	0.07	7	46
Cereals	Browntop millet	Brachiaria ramosa (L.)Stapf	0.68	±	0.03	0.90	±	0.08	0.86	±	0.24	5	46
	Wheat, durum	Triticum durum Desf.	0.65	±	0.03	0.80	±	0.05	0.87	±	0.07	3	100
	Quinoa	Chenopodium quinoa Willden.	0.63	±	0.03	0.80	±	0.03	0.68	±	0.07	11	100
	Teff	Eragrostis tef (Zucc.) Trot	0.62	±	0.01	0.69	±	0.05	0.69	±	0.11	9	67
Fruits and nuts	Almond	Prunus amygdalus Batsch.	0.00	±	0	0.94	±	0.07	1.00	±	0	8	100
	Cranberry	Vaccinium macrocarpon Ait.	0.72	±	0.02	0.85	±	0.07	0.87	±	0.2	10	100
	Sesame seed	Sesamum indicum L.	0.45	±	0.02	0.70	±	0.06	0.85	±	0.11	10	100
	Chinese boxthorn	Lycium chinense Miller	0.00	±	0	0.58	±	0.1	0.81	±	0.13	5	33
	Common fig	Ficus carica L.	0.43	±	0.02	0.58	±	0.04	0.67	±	0.05	12	100
Legumes	White Lupine	Lupinus albus L.	0.71	±	0.02	0.91	±	0.05	0.97	±	0.08	12	75
	Lentil	Lens culinaris Medikus	0.81	±	0.03	0.93	±	0.06	0.95	±	0.08	10	100
	Chick pea	Cicer arietinum	0.75	±	0.03	0.76	±	0.09	0.73	±	0.11	10	100
	Yellow Lupine	Lupinus luteus L.	0.59	±	0.02	0.73	±	0.04	0.80	±	0.08	10	71
Oilseeds	Sunflower	Helianthus annuus L v macro	0.68	±	0.02	0.75	±	0.07	0.72	±	0.12	1	29
Roots/ tubers	Chufa	Cyperus esculentus L.	0.95	±	0.03	0.99	±	0.01	0.96	±	0.08	6	50
Sugar crops	Sugar maple	Acer saccharum	0.52	±	0.02	0.74	±	0.08	0.79	±	0.15	1	54
Vegetables	Caper	Capparis spinosa	0.00	±	0	0.67	±	0.11	0.94	±	0.07	4	24
	Okra	Abelmoschus esculentus (L.)	0.31	±	0.02	0.59	±	0.04	0.68	±	0.13	4	29

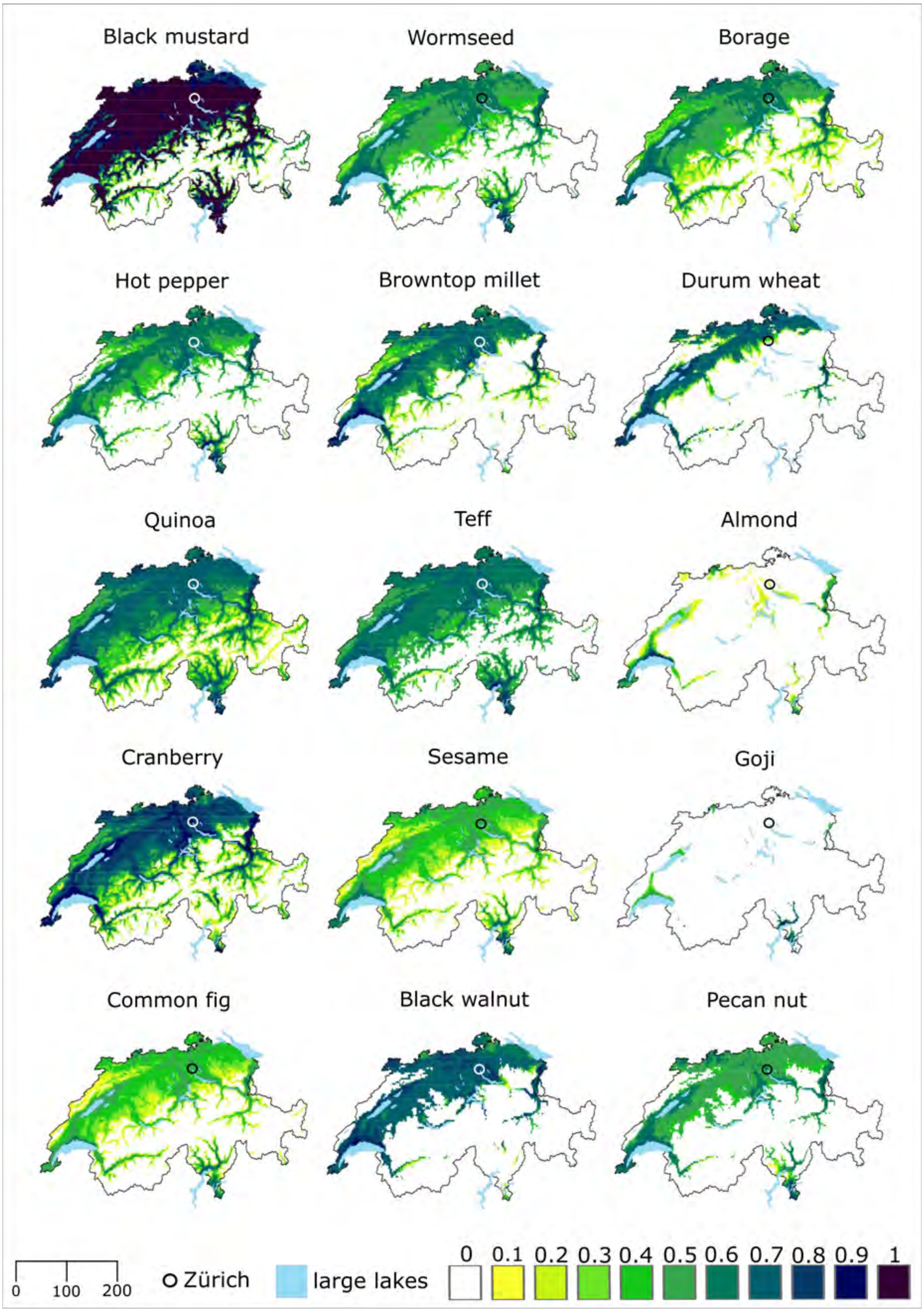

Figure 9: Climatic suitability in the reference period with historical climate data.

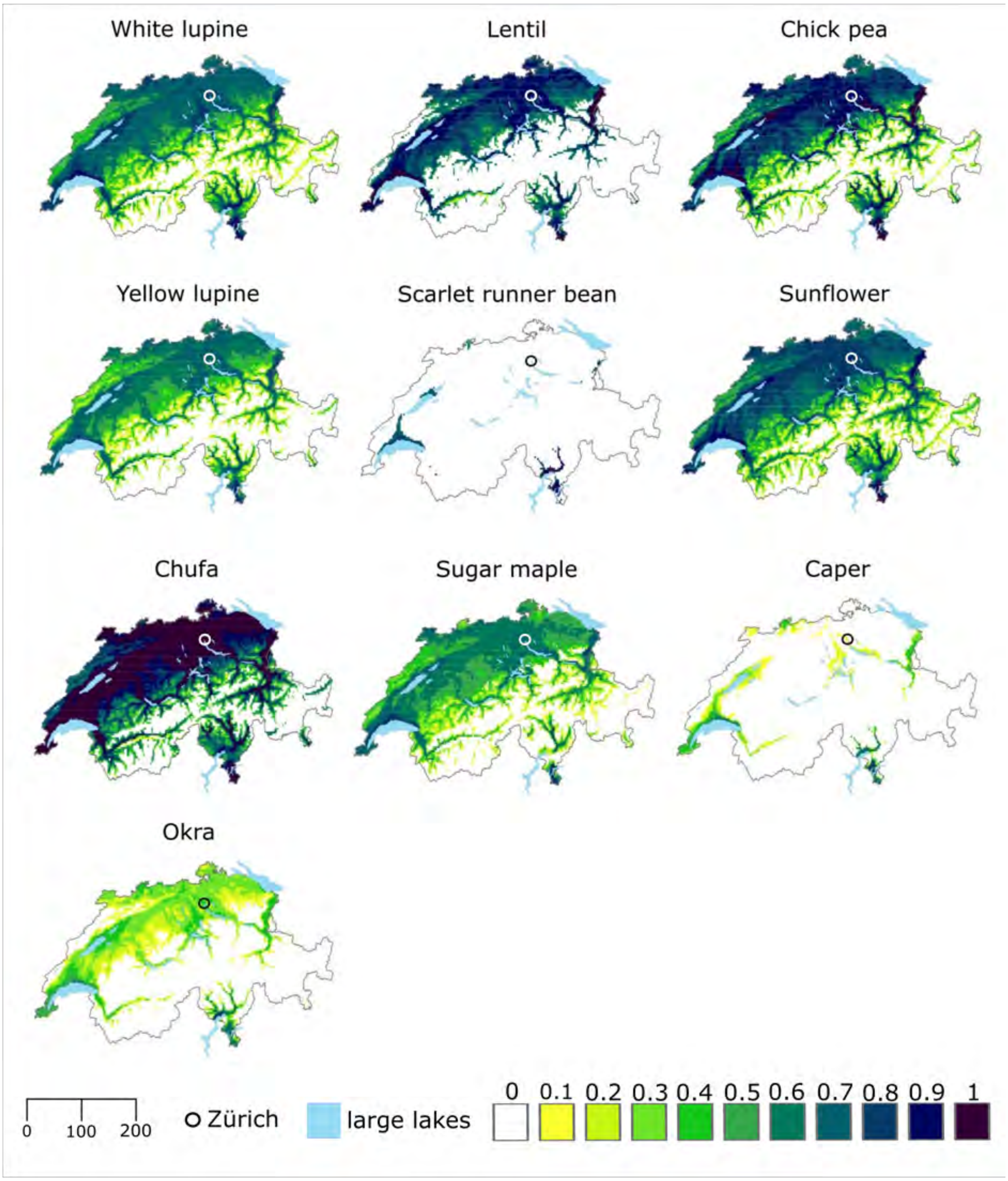

Figure 10: Climatic suitability in the reference period with historical climate data.

Table 5: Climatic suitability in the reference period under different data basis. Historical station-based data, historical grid-based data, projected data under RCP4.5 and projected data under RCP8.5.

	Suitability in the reference period (REF)			
Crop	Historical data station Zürich	Historical data in the map (station Zürich)	RCP4.5	RCP8.5
Black mustard	1	1	0.85	0.85
Wormseed	0.57	0.6	0.5	0.5
Borage	0.57	0.6	0.5	0.5
Hot pepper	0.58	0.6	0.56	0.56
Browntop millet	0.71	0.7	0.69	0.68
Quinoa	0.69	0.7	0.63	0.65
Durum wheat	0.04	0.35	0.65	0.63
Teff	0.63	0.7	0.62	0.62
Cranberry	0.78	0.8	0.73	0.72
Almond	0.17	0	0	0
Sesame seed	0.47	0.5	0.45	0.45
Chinese boxthorn	0	0	x	0
Black walnut	0.76	0.8	0.6	x
Pecan nut	0.53	0.55	0.44	x
Common fig	0.41	0.5	x	0.43
White lupine	0.76	0.8	0.71	0.71
Lentil	0.84	0.9	0.81	0.81
Chick pea	0.89	0.9	x	0.75
Yellow lupine	0.61	0.65	0.6	0.59
Scarlet runner bean	0	0	0	x
Sunflower	0.81	0.85	0.68	0.68
Chufa	1	1	0.95	0.95
Sugar maple	0.63	0.6	0.52	0.52
Caper	0.12	0	x	0
Okra	0.33	0.35	x	0.31

3.2 Suitability under different data basis

Table 5 displays the climatic suitability under different data basis to draw attention to the model chain bias of the projected climate data. Note, that for the third column with suitability values derived from map, in some cases, different values are achieved in the area where the Zürich station is located, so that the average value was taken in each case. All crops except durum wheat reach higher suitability values under the historical than under the projected climate data.

3.3 Selected crops

Beverage and spice crops

Black mustard

Tables 3 and 4 show the climatic suitability of black mustard for Zürich under RCP4.5 and RCP8.5. Under RCP4.5, the suitability is already high in the reference period (0.85) and increases further up to 0.98 in the second future period. Under RCP8.5, the suitability is high in the reference period (0.85) as well, and increases up to 0.98 in the first future period. The suitability slightly decreases down to 0.94 in the second future period. Tables 3 and 4 also show the standard deviation of the multi-model mean, that is, of the ten different model chains. Under RCP4.5, the variability is moderate in the reference period (0.06) and increases in the first future period. In the second future period, variability is the lowest. Under scenario 8.5, variability is moderate in the reference period but the lowest in the first and highest in the second future period (0.13). Figures 9 and 10 show the spatial climatic suitability in the reference period. High suitability values are reached all over the Central Plateau, around Lake Geneva and Lake Neuchâtel, as well as in the Rhône and Rhine valleys and in the Ticino (Figures 9 and 10). Black mustard represents a good source of 3 nutrients in total, which can be seen in Appendix A.4. It should be considered that only 29% of the nutritional information was available for this crop A.4).

Wormseed

Following pathway 4.5, wormseed is marginally suitable (0.5) in the reference period. The climatic suitability increases in the first (0.64) and second future period (0.68). Under scenario 8.5, wormseed shows a marginal suitability of 0.5 during the reference period. The climatic suitability increases more than under scenario 4.5 to 0.7 and 0.73 respectively in the future periods (Tables 3 and 4). Under scenario 4.5, the variability is relatively low over all periods, while it increases with time under RCP8.5 (Tables 3 and 4). Spatially, the climatic suitability in the reference period is reached in some parts of the Central Plateau, the Rhine valley, and in the Ticino (Figures 9 and 10). Wormseed is a good source for 14 nutrients (Appendix A.4).

Borage

In the reference period, borage has a marginal climatic suitability of 0.5 under both scenarios. Under RCP4.5, the climatic suitability increases in the first (0.64) and second future period (0.68). Following RCP8.5, the suitability increases first to 0.72 and slightly decreases in the second future period (0.62) (Tables 3 and 4). Under RCP4.5, the variability is low in the reference period and slightly elevated in future periods. Under scenario 8.5, the variability is low, except for the second future period, where it is particularly high with 0.22 (Tables 3 and 4). Across the Central Plateau, borage is marginally suitable. Exceptions can be found around Lake Geneva, Lake Neuchâtel, Lake Lucerne and Lake Zürich. The highest values are obtained at Lake Geneva but don't exceed 0.7 (Figures 9 and 10). Borage is seen as a good source for 14 nutrients (Appendix A.4).

Hot pepper

Hot pepper is marginally suitable in the reference period under both scenarios. Under scenario 4.5, hot pepper is suitable in the first (0.64) and second (0.7) future period. Following scenario 8.5, the model projects only a slightly higher suitability of 0.7 and 0.77 for the future periods (Tables 3 and 4). The variability under scenario 4.5 is low and only moderately elevated in the first future period. Under scenario 8.5, the variability increases with time (Tables 3 and 4). Hot pepper is climatically suitable in parts of the Central Plateau, especially around the major lakes, the Rhine valley and in the Ticino (Figures 9 and 10). As displayed in Appendix A.4, hot pepper is a good source of 7 nutrients.

Cereals

Browntop millet

Browntop millet has a climatic suitability of 0.69 under RCP4.5 and 0.68 under RCP8.5 in the reference period. Under scenario 4.5, the crop's suitability increases to 0.76 in the first future period and to 0.91 in the second future period. Following scenario 8.5, browntop millet is highly suitable in the first future period (0.9). The climatic suitability decreases slightly but stays high in the second future period (0.86) (Tables 3 and 4). Under RCP4.5, the variability is only 0.03 in the reference period, high in the first future period (0.22) and relatively high in the second future period (0.13). Under scenario 8.5, the variability increases with time, reaching 0.24 in the second future period (Tables 3 and 4). Browntop millet is climatically suitable for most of the Central Plateau. High suitability values can be obtained namely around Lake Geneva, Lake Neuchâtel and Lake Biel (Figures 9 and 10). Browntop millet represents a good source of 5 nutrients (Appendix A.4).

Durum wheat

Durum wheat has a climatic suitability of 0.65 in the reference period. Under scenario 4.5, the suitability increases to 0.72 in the first and to 0.76 in the second future period. Under scenario 8.5, the climatic suitability increases to 0.8, respectively 0.87, in the first and second future period (Tables 3 and 4). Under scenario 4.5, the variability is low in the reference period and relatively high in the future periods, reaching its peak in the first future period with 0.12. Under scenario 8.5, the variability moderately increases with time (Tables 3 and 4). Durum wheat is unsuitable for most of Switzerland. Along the axis from Geneva to Zürich, where values are reached at all, they are relatively high (Figures 9 and 10). For 3 out of 24 major nutrients durum wheat is considered a good source (Appendix A.4).

Quinoa

In the reference period, quinoa is climatically suitable with 0.63 in both periods. Under RCP4.5, the suitability slightly increases in the first (0.74) and second (0.77) future period. Following RCP8.5, quinoa is even highly suitable, with 0.8 in the first future period. In the second future period the suitability decreases to 0.68 (Tables 3 and 4). Under RCP4.5, the variability is low in all periods, while it is slightly increasing under RCP8.5 (Tables 3 and 4). Quinoa is suitable in most of the Central Plateau and the inner alpine valleys. At Lake Geneva, in the Rhine valley, and in the Ticino even a high suitability is reached (Figures 9 and 10). Quinoa is a good source of 11 nutrients (Appendix A.4).

Teff

In the reference period, Teff has a climatic suitability of 0.62. The suitability increases slightly and is 0.64 for the first and 0.69 for the second future period under RCP4.5. Under scenario 8.5, the climatic suitability is 0.69 for the future periods (Tables 3 and 4). Under scenario 4.5, variability is highest in the first future period with a moderate 0.08. Under scenario 8.5 variability increases in time and peaks in the second future period with 0.11 (Tables 3 and 4). Teff is suitable in most of the Central Plateau and at least marginally suitable at the alpine foothills and inner alpine valleys. In the Ticino and at Lake Geneva higher values are obtained (Figures 9 and 10). As displayed in Appendix A.4, teff is a good source for 9 nutrients.

Fruits and nuts

Almond

The Ecocrop model projects almonds to be unsuitable in the reference period. Following scenario 4.5, almonds are marginally suitable in the first and suitable in the second future period. Under RCP8.5, the suitability increases dramatically in the first future period (0.94) and is even higher in the second future period (1), describing almonds as climatically highly suitable (Tables 3 and 4). Under scenario 4.5, the variability between the model chains is very low in the reference period, then jumps to 0.22 in the first future period and decreases in the second future period to 0.17. The variability under RCP8.5 is 0 in the reference period and the second future period and slightly elevated in the first future period (Tables 3 and 4. Climatic unsuitability in Zürich in the reference period is reflected in Figures 9 and 10, in which nearly the whole of Switzerland is unsuitable.

Exceptions can be found around Lake Geneva, Lake Neuchâtel, the Rhine valley and the Ticino, where marginal suitability is reached. Almonds are a good source of 8 nutrients (Appendix A.4).

Cranberry

Under scenario 4.5, cranberries are climatically suitable in the reference (0.73) and first future period (0.76) and become even highly suitable (0.87) in the second future period. Following scenario 8.5, cranberries start with a similar suitability in the reference period (0.72) and become highly suitable in the first (0.85) and second future period (0.87) (Tables 3 and 4). The variability under scenario 4.5 is highest in the first future period and moderately elevated in the second future period. Under scenario 8.5, the variability increases with time and is relatively high in the second future period with 0.2 (Tables 3 and 4). At the Central Plateau, in the inner alpine valleys, around Lake Geneva, Lake Neuchâtel, and Lake Lucerne, cranberries are predominantly suitable. In some areas, especially around the major lakes, even high climatic suitability is reached (Figures 9 and 10). Cranberries represent a good source of 10 nutrients (Appendix A.4).

Sesame

In the reference period, sesame is only marginally suitable (0.45). Under scenario 4.5, sesame becomes suitable in the first (0.61) and second (0.69) future period. Under RCP8.5, the climatic suitability rises to 0.7 in the first future period and in the second future period sesame becomes even highly suitable (0.85) (Tables 3 and 4). The variability between the model chains under RCP4.5 slightly increases with time. Under scenario 8.5, the variability increases slightly more over time than under RCP4.5 (Tables 3 and 4). Sesame is very marginally to marginally suitable in most of Switzerland. Only around Lake Geneva and in the Ticino, climatic suitability is reached (Figures 9 and 10). Sesame is considered a good source for 10 nutrients (Appendix A.4).

Chinese boxthorn

Chinese boxthorn or goji berries are projected to have potential only under RCP8.5. In the reference period, they are unsuitable. The suitability rises to 0.6 in the first future period, and chinese boxthorn becomes even highly suitable in the second future period (Table 4). The variability increases with time and reaches a relatively high 0.13. The unsuitability in the reference period in Zürich is reflected all over Switzerland, besides some areas in the Ticino and around Lake Geneva (Figures 9 and 10). Only single grid cells in the Ticino reach suitability values at all. As displayed in Appendix A.4, the berries are a good source of 5 nutrients.

Common fig

Common fig is projected to have potential only under RCP8.5. In the reference period, common figs are only marginally suitable (0.43). The climatic suitability rises to 0.6 in the first future period and to 0.67 in the second future period, projecting common fig to be suitable for the climatic conditions (Table 4). The variability slightly increases with time. Common fig is very marginally to marginally suitable for most of Switzerland, besides some areas in the Ticino and around Lake Geneva, where common figs are suitable (Figures 9 and 10). Common fig represents a good source of 12 nutrients (Appendix A.4).

Black walnut

Black walnut is projected to have potential only under RCP4.5. In all periods, black walnut is climatically suitable with 0.6, 0.69 and 0.72, respectively (Table 3). The variability is low, except for the first future period, where it moderately increases (0.08). Black walnut is climatically suitable in the Central Plateau. In some areas, around Lake Geneva, Basel or Lake Zürich, high suitability is reached (Figures 9 and 10). Black walnut is a good source of 3 nutrients (Appendix A.4).

Pecan nut

Pecan nut is projected to have potential only under RCP4.5. In the reference period, pecan nut is climatically only marginally suitable (0.44). In the first and second future period, the crop is projected to be suitable with 0.61 and 0.75, respectively (Table 3). The variability is moderately increased in future periods. Pecan nut is marginally suitable in most of Switzerland with few exceptions around the major lakes, the Ticino and Rhine valley (Figures 9 and 10). Pecan nut is considered a good source of 4 nutrients (Appendix A.4).

Legumes

White lupine

White lupine is already suitable in the reference period (0.71) under both scenarios and under RCP4.5 highly suitable in the first (0.86) and second (0.9) future period. Similar values are obtained following RCP8.5 where the crop even reaches 0.91, respectively 0.97, in the future periods (Tables 3 and 4). The variability under scenario 4.5 is moderately increased in future periods. Under RCP8.5, the variability increases with time but remains moderate (Tables 3 and 4). White lupine is suitable across the Central Plateau and inner alpine valleys. Around the large lakes, the Rhine valley and in the Ticino high suitability is reached (Figures 9 and 10). The legume is seen as a good source of 12 nutrients (Appendix A.4).

Lentil

The model projects that lentils are highly suitable in all periods and under both scenarios, with values increasing in time. The climatic suitability is 0.81 in the reference period under both scenarios. Under scenario 4.5, lentil is highly suitable, with 0.86 in the first future period and 0.94 in the second future period. The climatic suitability under scenario 8.5 in the first future period is 0.93 and increases even further to 0.95 in the second future period (Tables 3 and 4). The variability under RCP4.5 is highest in the first future period (0.07). The variability under RCP8.5 increases with time but remains moderate (Tables 3 and 4). The high suitability values obtained at station Zürich can also be observed in Figures 9 and 10, where the entire Central Plateau, the inner alpine valleys and the Ticino are suitable to highly suitable. As displayed in Appendix A.4, lentils are a good source of 10 nutrients.

Chick pea

Chick pea is projected to have potential only under RCP8.5. In the reference period, the crop has a suitability of 0.75. In the first future period chick pea is highly suitable (0.8) and in the second future period suitable (0.73) (Table 4). The variability increases with time and peaks with a relatively high 0.11 in the second future period. Chick pea is suitable and even highly suitable throughout the Central Plateau, the inner alpine valleys and in the Ticino. Marginal suitability is reached on the alpine foothills (Figures 9 and 10). The legume represents a good source of 10 nutrients (Appendix A.4).

Yellow lupine

Under RCP4.5, yellow lupine is projected to be suitable (0.6) in the reference period and 0.69 and 0.72 in the future periods, respectively. Following scenario 8.5, the climatic suitability is only marginal in the reference period (0.59), suitable in the first (0.73) and highly suitable in the second future period (0.8) (Tables 3 and 4). Under RCP4.5, the variability is low in all periods. Under RCP8.5, the variability increases moderately over time (Tables 3 and 4). Large parts of the Central Plateau are climatically suitable, as well as the inner alpine valleys and the Ticino 9 and 10. Yellow lupine is a good source of 10 nutrients (Appendix A.4).

Scarlet runner bean

Scarlet runner bean is projected to have potential only under RCP4.5. In the reference period, the crop is climatically unsuitable. Scarlet runner bean is predicted to be marginally suitable (0.52) in the first future period and suitable (0.74) in the second future period (Table 3). Variability is 0 in the reference period and jumps to a very high 0.36 in the first future period and slightly decreases on a high level to 0.27 in the second future period

(Table 3). Scarlet runner bean is unsuitable throughout most of Switzerland. Marginal climatic suitability is only achieved around Lake Geneva and in the Ticino (Figures 9 and 10). The crop is a good source of one nutrient (Appendix A.4), although the low level of available information on nutritional quality should be considered (16%).

Oilseeds

Sunflower

The crop is climatically suitable in the reference period (0.68). Under scenario 4.5, suitability slightly increases in the first (0.71) and second (0.74) future period. Similar values are obtained under RCP8.5 in the first (0.7) and second (0.72) future period (Tables 3 and 4). The variability under RCP4.5 is highest in the first future period with a relatively high value of 0.12 and moderate in the second future period with 0.08. Under RCP8.5, the variability increases with time and peaks with relatively high 0.12 (Tables 3 and 4). Throughout Switzerland, except for the alpine region, climatic suitability is given. High climatic suitability is reached in large parts of the Central Plateau, in the Rhine valley and in the Ticino (Figures 9 and 10). Sunflowers are only considered a good source of one nutrient (Appendix A.4), although the low level of available information on nutritional quality (29%) should be considered.

Root and tuber crops

Chufa

In the reference period, chufa has a high suitability (0.95). Under scenario 4.5, suitability increases even further in the future periods with 0.96 and 0.98, respectively. Under RCP8.5, the climatic suitability also increases in the first future period (0.99) and decreases slightly but remains high in the second future period (0.96) (Tables 3 and 4). Under RCP4.5, the variability is moderate except for the first future period, which is relatively high with 0.11. Under RCP8.5, the variability is low, except for moderate 0.08 in the second future period (Tables 3 and 4). Chufa is at least suitable throughout the whole of Switzerland except the Alps. High suitability is reached in almost the entire Central Plateau, in the Rhine valley and in the Ticino (Figures 9 and 10). Chufa represents a good source for 6 nutrients (Appendix A.4).

Sugar crops

Sugar maple

In the reference period, sugar maple is only marginally suitable (0.52). Under scenario 4.5, sugar maple becomes climatically suitable with 0.62 in the first and 0.73 in the second future period. Under RCP8.5, the suitability increases in the first (0.74) and second future period (0.79) (Tables 3 and 4). The variability between the model chains under scenario 4.5 is moderate except for the first future period, where it is relatively high with 0.12. Under scenario 8.5, the variability increases with time, reaching its relatively high peak with 0.15 in the second future period (Tables 3 and 4). Sugar maple is suitable in large parts of the Central Plateau, the Rhine valley and some parts in the Ticino (Figures 9 and 10). Sugar maple is seen as a good source of one nutrient (Appendix A.4).

Vegetables

Caper

Caper is projected to have potential only under RCP8.5. In the reference period, the crop is unsuitable, but the climatic suitability increases in the first future period (0.7) and even reaches high suitability (0.94) in the second future period (Table 4). The variability is 0 in the reference period, peaks with a relatively high 0.11 in the first future period and is moderate in the second future period. Like in the reference period at station Zürich, caper is projected to be unsuitable for the whole of Switzerland (Figures 9 and 10). Only around Lake Geneva and in the Ticino marginal or moderate suitability values can be obtained. The crop represents a good source of 4 nutrients (Appendix A.4), although it should be considered that information on the nutritional quality was only available for 24%.

Okra

Okra is projected to have potential only under RCP8.5. In the reference period, okra is very marginally suitable (0.31). The crop becomes marginally suitable in the first future period (0.59) and suitable in the second (0.68) future period (Table 4). The variability increases with time and reaches a relatively high 0.13 in the second future period. Okra is very marginally to marginally suitable in most of Switzerland. Only at Lake Geneva and in the Ticino, marginal to moderate suitability values can be obtained (Figures 9 and 10). Okra is a good source of 4 nutrients (Appendix A.4), although it should be considered that only 29% of the information on nutritional quality was available.

4 Discussion

4.1 Potential crops for station Zürich

The crops presented in Tables 3 and 4 are now briefly introduced and then discussed according to the three pillars of sustainability, a concept first mentioned in the 1970s (Purvis *et al.*, 2019). According to the idea of the three pillars, a concept, process or project is sustainable if it considers the interactions between ecological, environmental and social systems and strives to strengthen all three areas.

1. The level of ecological sustainability is determined by the climatic suitability, the need for irrigation, fertilisation, and the sensitivity to pests, weeds and diseases.
2. Economical sustainability in this case is defined by the labor required, additional equipment or further processing that may be required, market potential and demand.
3. Social sustainability in this framework is discussed exclusively in relation with nutritional quality.

Beverage and spice crops

<u>Black mustard</u>
The seeds of this black variety can be used as a spice, either whole or grounded. The leaves and the stem can be eaten as well. It can be found in Northern Africa, Southern Europe, and Asia. Black mustard requires an open, sunny position and can be cultivated on many soil types while growing best on well-drained and light sandy loams (Plants for a future, 2021, as cited in Simons, 1977). According to Duke (1983) as cited in Plants for a future (2021) the crop is adapted to a broad range of climatic conditions but is mostly grown in temperate regions with low to moderate rainfall. The model results indicate that black mustard is already today climatically well adapted and will be even more in the future. Although on a high level, it should be mentioned that the suitability decreases in the second future period, indicating that ongoing climate change would have a negative impact. The variability between the model chains is moderate except for the first future period under RCP4.5 and the second future period under RCP8.5. This uncertainty comes with a higher risk for the farmers. Black mustard can be sown in early spring. It germinates quickly and proliferates, making it an excellent green manure crop that can be sown in late summer. The harvest is challenging since the seeds are rapidly shed when they are ripe (Plants for a future, 2021). Due to the low level of available information, no conclusive statement on the nutritional quality is possible.

Wormseed

The herb wormseed, or "epazote herb", is used as a tea substitute and originates from tropical to subtropical regions in South- and Central America. Wormseed is growing wild in Europe, for example, in Switzerland on debris sites and wasteland (Info Flora, 2021). Wormseed prefers full sunlight and fertile soil but is reported to succeed in most soils (Huxley 1992 as cited in Plants for a future, 2021). In Europe it grows as an annual plant, since it is not hardy (Bown, 1995, as cited in Plants for a future, 2021). Wormseed is a C4 plant, so it is well adapted to hot and dry environments, as they have a high water use efficiency. The model projects moderate but increasing climatic suitability. Higher values can be obtained under RCP8.5, suggesting that the crop will benefit from unmitigated climate change in Switzerland. The relatively low variability between the model chains indicates a certain degree of confidence in the results so that the cultivation risk for farmers is reduced. Regarding the 25 selected crops' nutritional quality, only borage is a good source of as many nutrients as wormseed. Wormseed could be marketed as a "superfood", as it provides sufficient amounts of 14 nutrients.

Borage

Borage is an annual herb whose aromatic leaves are used as a spice similar to oregano or thyme (Morton, 1992). Furthermore, it is cultivated for its seed oil, which is marketed as "starflower oil" (Gardner *et al.*, 2021). Being native in subtropical, dry climates, it is frost tender. Borage requires well-drained soils and somewhat shady conditions. According to the model results, borage is suitable for climatic conditions in the future. Under unmitigated climate change (RCP8.5), the suitability drops in the second future period, indicating that ongoing climate change would decrease the crop's potential. Under RCP8.5, the model chain uncertainty is high in the second future period, indicating that the cultivation could be considered risky for farmers. In the other periods, the variability is low to moderate. Like wormseed, borage is a good source for 14 nutrients, opening the potential of selling it as a "superfood".

Hot pepper

Hot pepper is a wild chilli pepper native to Central America (Carvalho *et al.*, 2014). A well-known domesticated variety is the "Tabasco pepper". The crop requires a sunny and warm position and a well-drained and fertile soil (Plants for a future, 2021). According to Masefield *et al.* (1981) as cited in Plants for a future (2021), the species is frost tender and therefore often cultivated as an annual plant. The suitability is marginal first and increases over time under both scenarios, indicating that hot pepper will be more suitable under climate change conditions. The relatively low variability between the model chains indicates a certain degree of confidence in the results so that the cultivation risk for farmers is reduced. Hot pepper has a relatively high nutritional quality and contains particularly much vitamin C.

Cereals

Browntop millet

This cereal is an important staple food in India. It can be found in semi-arid tropics and warm tempered regions. According to the United States Department of Agriculture Natural Resources Conversation Service (2014), Browntop millet grows well in shallow and rocky soils and being a C4 plant, it is suitable for dry conditions. Higher yields may be obtained when the crop is irrigated. It can be sown in late spring and thrives in full sun and well-drained soils. Potential pests are armyworms, grasshoppers and the mung bean yellow mosaic bigeminivirus (United States Department of Agriculture Natural Resources Conversation Service, 2014). Millets can be useful as green manure to protect and nurture the soil as little seed is required (A. Aebi, personal communication). North of the Jura mountains, proso millet is cultivated as a second crop after the main crop, like spelt or pea. The crop's main purpose is to act as green manure and protect the soil, so no weed control or fertilisation is required. Due to late sowing, yields of 10-12 kg/are (100 m^2) may not be ideal, but millet serves as a safety net and is cheap and easy to grow (Anonymous, personal communication). Browntop millet's suitability increases in the future. While under RCP4.5, its suitability increases over time, it decreases under RCP8.5, indicating that unmitigated climate change will have a negative impact. Variability is high under RCP4.5 in the first future period and under RCP8.5 in the second future period. The deviation from the multi-model mean is 0.22, respectively 0.24. Thus, the suitability values should be viewed critically and point to an increased cultivation risk. Special mechanisation is needed to peel the grains, which might be a hurdle for farmers who produce only small quantities. Browntop millet has a moderate nutritional quality.

Durum wheat

Durum wheat is a widely cultivated wheat species and primarily used to make pasta. It is cultivated in China, North America and Southern Europe, where the northern limit is Northern Italy (Morari *et al.*, 2018). The species is more sensitive than common wheat. The summer variety can be sown from February to March, depending on the soil, since it must be warm enough (Roth and Erkens, 2018). Sufficient nitrogen fertilisation is recommended, especially in the early stages of development, taking care of course not to cause air or water pollution (Morari *et al.*, 2018). For the cultivation, an area with little weed pressure should be selected, as durum wheat shows low competitive strength, especially in the beginning. According to Roth and Erkens (2018), durum wheat is particularly susceptible to fungi such as fusaria. Its climatic suitability is moderate in the reference period and increases over time under both scenarios. Under RCP8.5, the suitability is exceptionally high, indicating that the crop would benefit from Switzerland's climatic changes. Under RCP4.5, variability in the first future period is relatively high with 0.12, and therefore, the results should be viewed critically. However, since this period's suitability is 0.72, even a deviation of -0.12 would still represent suitable conditions. Durum wheat does not have a very high nutritional quality, but there is generally a high demand since it is mainly made into pasta. The low competitive strength, the sensibility towards fungi and uncertain potential in the future should be considered when planning on cultivating this crop.

Quinoa

Quinoa is a gluten-free pseudocereal from South America, more precisely the Andean region (Jancurová *et al.*, 2009). According to Jacobsen (2003), there is high potential for growing quinoa in Southern Europe, while further north the plant's short growing season and limited frost tolerance are constraints. Quinoa grows on rocky and nutrient-poor soils and is drought resistant due to its deep rooting. Intensive rainfall and heavy soils pose unfavourable conditions (Bachmann and Maciejok, 2018). Erfurt (2018) discusses the optimal management of quinoa, whose cultivation is demanding and risky. It requires sufficient nitrogen, especially in the first development stages. An area with little weed pressure should be selected as quinoa shows low competitive strength. Quinoa must be sown early to avoid being mistaken for or mixed with a prominent local weed called Chenopodium album (S. Brunner, personal communication). According to S. Brunner (personal communication), irrigation is unnecessary, but nitrogen fertilisation (80 kg/ha or more) positively affects the yield. Harvesting between the end of July and the beginning of August should be done as early as possible as the quality decreases, the longer one waits. A cold and wet spring can cause the harvest to be lost (S. Brunner, personal communication). At the farmer's location between Bern and Biel, a yield of 1-2.5 t/ha can be achieved. In a field trial conducted by Agroscope in Changins, yields of 1-2.5 t/ha were achieved with different quinoa varieties in 2018 (Levy *et al.*, 2019). The Strickhof Research Centre achieved a yield of 2,5 t/ha with fertilisation and 1,9 t/ha without fertilisation in a field trial in Wülflingen in 2018 (Strickhof, 2019). These reports and trials paint a positive picture of quinoa cultivation potential in Switzerland. Under RCP4.5, the climatic suitability is moderate and increases over time. Under RCP8.5, the suitability is high in the first future period and decreases afterwards, showing that unmitigated climate change will have a negative impact. The variability is very low, indicating rather stable cultivation conditions. Bachmann and Maciejok (2018) state that processing of the yield is complex and expensive, especially for small quantities. The increasing international demand has impacted the price. As a result, quinoa has become partly unaffordable for the local population in South America (Bachmann and Maciejok, 2018). Organisations like IP-Suisse and Biofarm therefore welcome the cultivation of Swiss quinoa. The nutritional value, especially the protein content, is higher than in most cereals (Jancurová *et al.*, 2009). In addition, quinoa is gluten-free, which makes it attractive for people with a gluten-intolerance.

<u>Teff</u>

Teff is cultivated in Southern Africa, especially in Ethiopia, where it is processed to Injera, bread and local staple food. Teff succeeds in humus-rich and loamy soils and requires a sunny position and a well-weeded field (Plants for a future, 2021). The crop uses the C4 carbon fixation and is therefore well adapted to dry conditions. Gebremariam *et al.* (2014) state that teff represents a reliable and low-risk cereal with few diseases that tolerates even harsh environments. According to the model results, its climatic suitability is moderate and increases only slightly in the future. The variability is relatively high under RCP8.5 in the second future period, indicating an increased production risk. According to Gebremariam *et al.* (2014), teff includes all essential amino acids and has a high nutrient composition in general which is reflected in Appendix A.4.

Fruits and nuts

<u>Almond</u>

The tree originates from Central Asia. Today it can be found in the Mediterranean area, Central Asia and the United States (Reutimann *et al.*, 2020). Almond trees require sandy loam with high permeability. They are very resistant to drought and are winter hardy. According to Reutimann *et al.* (2020), they can be grown in Switzerland in the same areas as vines and apricots. A possible limitation of cultivation in Switzerland compared to the Mediterranean region is the higher humidity, which could favour diseases such as monilia (Reutimann *et al.*, 2020). The climatic suitability of almond, which is unsuitable in the reference period, increases rapidly and steeply in the future periods, especially under RCP8.5. The variability under RCP4.5 is high in the future periods, especially in the first one. These results suggest that moderate climatic changes would lead to highly alternating suitability and thus higher production risk, while extreme climate changes could increase almonds' potential. The nuts have a relatively high nutritional quality and contain high amounts of vitamin E in particular. Despite possible difficulties in cultivation and the competition in quality and price compared to imports, it could have potential, marketed as a "Swiss almond" (Reutimann *et al.*, 2020).

Cranberry

Cranberries can be eaten fresh or dried and are also processed into juice. They are found in North America, Asia and Europe. According to Huxley (1992), as cited in Plants for a future (2021) they require humus-rich, light sandy and well-drained soils and prefer semi-shady positions. Cranberries can grow on nutrient-poor and acidic soils (Huxley, 1992, as cited in Plants for a future, 2021). The crop takes five years to come to full bearing and can be used for up to 100 years (Huxley, 1992, as cited in Plants for a future, 2021). The parasitic fungus Exobasidium perenne can colonise the leaves. Cranberry's climatic suitability increases in the future and becomes high under both scenarios, where scenario 8.5 produces slightly higher values. The results hence indicate that unmitigated climate change will benefit the crop. However, the variability between the model chains is relatively high in future periods, especially under RCP8.5, suggesting increasingly inaccurate results and higher cropping risk under unabated climate change. Cranberries have a high nutritional quality and contain particularly much vitamin C.

Sesame

The edible seeds of sesame are used fresh, roasted or processed to tahini paste or oil. Sesame originates from India and can today be found in all tropical to warm-tempered regions (Bown, 1995, as cited in Plants for a future, 2021). The annual crop requires a well-drained, somewhat dry, and porous soil. Furthermore, a sunny position is favourable while heavy rains might increase the risk of fungal diseases (Bown, 1995, as cited in Plants for a future, 2021 and Yermanos, 2015). According to Yermanos (2015), sesame performs best when temperatures are high during the entire growing season, while frost occurring before maturity would kill the plant. The suitability values are moderate under RCP4.5 and increase under RCP8.5, which is even high in the second future period. During this period, the variability also increases which means more significant uncertainty for farmers in terms of cultivation. Sesame has a high nutritional quality, providing many essential minerals and vitamins in sufficient amounts (Appendix A.4).

Chinese boxthorn

The fruit of chinese boxthorn, known as goji berry, is eaten fresh or dried and can also be consumed as a tea. It originates from China and spreads across warm and subtropical regions in Southeast Asia and gained popularity as a so-called "superfood" (Zhang *et al.*, 2010). It does not require rich soil, but a well-drained one in a sunny position (Huxley, 1992, as cited in Plants for a future, 2021). The model results show that the climatic suitability of chinese boxthorn is only reached in the future periods under RCP8.5. The variability increases with time and is relatively high in the future periods, indicating a higher production risk, especially in the first future period where the suitability is only marginal. Since the goji berries are not known fresh but only dried on the European market, they must be dried, which can be time-consuming and costly (D. Schulthess, personal communication). The berry has a relatively high nutritional quality, considering the low level of available information.

Common fig

According to Crisosto *et al.* (2011), fig trees are found in moderate climatic regions and can either be eaten fresh or dried. Fresh consumption requires nearby cultivation as figs are very sensitive to damage and postharvest infections (Crisosto *et al.*, 2011). Common figs prefer a sunny position and are winter hardy, although the top may be damaged through frost (Davis, 1990, as cited in Plants for a future, 2021). They prefer a well-drained medium loam and can succeed in dry soil. The climatic suitability is rather moderate and only given in the future periods under RCP8.5. The variability is very low which indicates rather stable conditions and conclusive results. The unsuitability in the reference period is somewhat surprising as figs are already cultivated in Northern Switzerland (N.A., 2017). According to Boos and Huistein (2003), successful cultivation depends strongly on the cultivar. The type of pollination and fertilisation should be considered as not every variety can thrive in Northern Switzerland. Figs have a high nutritional quality and provide many essential vitamins and minerals (Appendix A.4).

Black walnut

Black walnut is native to the Eastern United States and cultivated for its edible nuts (Michler *et al.*, 2007). According to Michler *et al.* (2007), the tree is shade intolerant and prefers deep, fertile, well-drained and loamy soils. A toxic chemical occurs in the roots, bark, leaves, and nut husks, so certain crops should not be grown nearby (Michler *et al.*, 2007). The climatic suitability is relatively moderate and only given under RCP4.5, indicating that unabated climate change would not benefit this crop. The variability is low and only slightly increased in the first future period, indicating relatively stable growing conditions for black walnut. The nutritional quality of the crop is moderate.

Pecan nut

Pecan is a tree native to the United States and Mexico and cultivated for its edible nuts. According to Fronza *et al.* (2018), pecan prefers deep and well-drained soils with a high level of nutrients and good water holding capacity. Poorly drained soils are unfavourable as excess moisture causes stress to the root system (Fronza *et al.*, 2018). The crop is susceptible to pests like phylloxera or fungi like Fusicladium effusum. Since there is no method yet to control the disease, preventive measures like choosing a cultivar with a higher resistance should be taken into consideration (Fronza *et al.*, 2018). The climatic suitability is relatively moderate and only given under RCP4.5. The suitability increases over time, but as pecan is not suitable under RCP8.5, the results indicate that unmitigated climate change would decrease the crop's potential. The variability is low and only slightly elevated in the future periods, which speaks for the results' certainty. Pecan nuts have a moderate nutritional quality.

Legumes

<u>White lupine</u>

White lupine originates from the Mediterranean area and can today be found in South America, Southern Africa and Southern Europe. According to Facciola (1990), as cited in Plants for a future (2021) the legume is used like cooked beans or roasted and grounded into flour. Due to their high protein levels, they are a promising substitute for soybean in the vegetarian diet (Frick *et al.*, 2002, as cited in Heine *et al.*, 2018). White lupines are less heat-dependent than soybeans and grow best in acidic soils, as they are very susceptible to lime (Biasio, 2020). Due to their long roots, they can tolerate dry conditions. White lupine does not compete well with weeds and is very susceptible to anthracnose, so particular varieties like "Frieda" or "Sulimo" are needed, especially for organic farming (Frick *et al.*, 2002). The research centre Strickhof conducted field experiments near Winterthur for different varieties in 2019 and 2020, where yields of 3.4-4.2 t/ha were achieved (Carrel and Zingg, 2020). Like all legumes, white lupine has root nodules that fix nitrogen and therefore, no further fertilisation is necessary. The climatic suitability is already achieved in the reference period and increases over time, especially under RCP8.5. Near-optimal climatic suitability is achieved, indicating that white lupine will benefit from ongoing climate changes in Switzerland. The variability is low and only slightly elevated in the future periods, which speaks for the results' certainty. White lupine has a high nutritional quality.

<u>Lentil</u>

Lentils are often eaten cooked or in soups and stews. They are mostly cultivated in warm temperate to tropical regions in South Asia, North America and Eastern Africa (Reda, 2015). Cultivation in Switzerland was abandoned at the end of the 1940s and the knowledge about cultivation was lost (Strickhof, 2019). Lentils grow in sunny positions and require medium-heavy soils with a fine surface (Huxley, 1992, as cited in Plants for a future, 2021). They are suitable for mixed cropping and require support crops like pea (Erfurt, 2018). They should preferably be cultivated on weed-free fields and be sown early. Lentils need to be dried after the harvest. Due to their root nodules they can fix nitrogen and do not need further fertilisation. Lentils of the green variety "Anicia" are currently cultivated north of the Jura mountains. They are reported as not very demanding and tolerant to dry conditions (Anonymous, personal communication). At the farmer's site, lentils are grown together with camelina which covers the soil and prevents weeds. Threshing can be a bit complicated as it must be done in time to separate the grains properly. Yields of 10-15 kg/are (100m^2) can be achieved (Anonymous, personal communication). According to the farmer, lentils are a niche product but the demand exists and they can be sold via Biofarm. The Strickhof Research Centre conducted field trials with the varieties "Anicia" and "Beluga". The crops did not require any care and produced good yields of 2.2-2.9 t/ha, depending on the supporting crop (Strickhof, 2019). The climatic suitability is high and will increase over time, especially under RCP8.5 where almost optimal climatic suitability is reached, indicating that lentils will profit from Switzerland's ongoing climatic changes. The variability is slightly increased in the future periods, indicating a mild increase in the results' uncertainty. Lentils have a high nutritional quality.

Chick pea

Chick peas are eaten cooked or processed to hummus or falafel. The annual legume is grown in subtropical and Mediterranean regions worldwide. Chick pea requires a sunny position and rather well-drained soil (Meier, 2020). Wet or shady locations are unfavourable. The crop is drought resistant and frost tender. According to Meier (2020), chickpeas have low competitiveness, so weed control is crucial. Due to their root nodules they can fix nitrogen and do not need further fertilisation. Chick peas are already cultivated north of the Jura mountains. As their competitive strength is deficient, weeds are a problem. This is especially the case if weed germination shifts to the main crop due to dry springs which causes more damage. To counteract the competitive weakness, one could increase the spacing (Anonymous, personal communication). The climatic suitability is moderate in the reference period and only given under RCP8.5. The suitability becomes high in the first future period and decreases afterwards, suggesting that the climatic conditions are becoming less favourable. Variability between the model chains is increasing over time, creating an expanding production risk for the farmers.

Yellow lupine

Like the white lupine, the yellow lupine originates from the Mediterranean region and can be found in South America today as well. It is often eaten as a pickled snack. Yellow lupine requires acidic soil and a sunny position (Huxley, 1992, as cited in Plants for a future, 2021). According to Frick *et al.* (2002), only the white and blue lupine are interesting for Switzerland's cultivation, but it has to be mentioned that this statement is based on today's climate. The climatic suitability projected by the model is moderate in the first future period under both scenarios and becomes high in the second future period under scenario 8.5. The results indicate that unmitigated climate change would benefit the climatic suitability of yellow lupine. The variability is low under RCP4.5 and slightly elevated in the future periods under RCP8.5, indicating that unmitigated climate change increases farmers' cultivation risks. Yellow lupine has a high nutritional quality and the highest INQ for protein of all 25 crops (although the INQ is lower than 1).

<u>Scarlet runner bean</u>
Scarlet runner bean is a legume from Central America. According to Hamburdă *et al.* (2016), it ranks third on worldwide importance in the Phaseolus group (beans). As the roots cannot withstand low temperatures in winter, it is mostly cultivated as an annual plant (Hamburdă *et al.*, 2016). Scarlet runner bean can fix nitrogen itself and therefore does not need fertilisation. The legume requires a sunny position in a well-drained and rich soil (Huxley, 1992, as cited in Plants for a future, 2021). Scarlet runner bean is unsuitable in the reference period, and suitability in the future periods is only given under RCP4.5. The results suggest that moderate warming is beneficial for the crop, but unabated climate change is not. The variability is very high in the future periods, especially in the first future period. Therefore, the suitability values are relatively uncertain and indicate a high production risk. According to Schwember *et al.* (2017), the cultivation of scarlet runner bean is labour-intensive and requires much material, as the climbers need a supporting structure to grow. However, Heine *et al.* (2018) present the legume as one alternative to soy as a plant-based protein source. Due to the low level of available information, no conclusive statement on the nutritional quality is possible.

Oilseeds

<u>Sunflower</u>
Sunflower originates from the Americas and is today also cultivated in Europe. The seeds are eaten or processed to sunflower oil. According to Duke (1983), as cited in Plants for a future (2021) sunflower grows best on deep and rich soils, while it is intolerant of acidic soils or waterlogging. Sunflowers require a sunny position (Dirr and Heuser, 1987). Sunflowers are an exception in this selection since they are not alternative crops. They have been cultivated in Switzerland before, but cultivation has fallen sharply in recent decades, and the focus has been on rapeseed, which is easier to cultivate (Ingold, 2017). The domestic demand for sunflower oil could not be met. However, cultivation is on the rise again, not least because of subsidies provided by the federal government to meet the domestic demand again (Ingold, 2017). Therefore, and because there was simply no alternative potential crop in this category, sunflowers are discussed as well. The climatic

suitability is slightly increasing over time but stays moderate. Under scenario 4.5, higher values are obtained, indicating that unmitigated climate change would not benefit this crop. The variability is relatively high in the first future period under RCP4.5 and in the second future period under RCP8.5. This uncertainty should be considered when cultivation is contemplated. Due to the low level of available information, no conclusive statement on the nutritional quality is possible.

Root and tuber crops

Chufa

Chufa or tiger nut is cultivated for its tubers that can be eaten either fresh or dried. It is found in warm temperate and tropical regions (Dirr and Heuser, 1987, as cited in Plants for a future, 2021). According to Dirr and Heuser (1987), as cited in Plants for a future (2021) chufa requires a moist sandy loam and sufficient irrigation. They are frost tender and should therefore rather be cultivated as an annual crop. Chufa has a high climatic suitability throughout all periods and under all scenarios. While the values increase over time under RCP4.5, the suitability slightly decreases in the second future period under RCP8.5. These findings suggest that although the suitability is still high, unmitigated climate change will decrease the crop's potential in the future. The variability in the first future period under RCP4.5 is relatively high. However, a deviation of -0.11 would not change the high suitability of 0.96, as it would still be above 0.8. This crop's cultivation can only take place under safety measures since it is on the blacklist for invasive species in Switzerland (Info Flora, 2021). Chufa has a relatively high nutritional quality.

Sugar crops

Sugar maple

The sugar maple tree is cultivated in North America for its sap. The sap contains a large proportion of sugar, which can be processed into maple syrup. According to Gordon and Rowe (1982), as cited in Plants for a future (2021) sugar maple grows on well-drained, but moist soils. In late winter or early spring, the sap can be harvested favourably on a sunny day after a frost (Weiner, 1980, as cited in Plants for a future, 2021). The climatic suitability is increasing over time but stays moderate. Under RCP8.5, higher values are obtained, indicating that unmitigated climate change will benefit this crop. The results were somewhat surprising, as sugar maple is not a subtropical or mediterranean crop like many other crops on the list. The variability between the model chains increases over time, which requires a critical assessment of the suitability results and indicates an increasing production risk. As it is a sugar crop, low nutrient quality is expected and not classified as a weakness.

Vegetables

Caper

Caper is grown for its flower buds that are eaten pickled. The crop can be found in the Middle East and the Mediterranean area. According to Huxley (1992) as cited in Plants for a future (2021), capers are heat and drought-tolerant and require hot and relatively dry positions in full sun to grow. The perennial crop thrives on non-stratified loamy soils and is frost tender (Huxley, 1992, as cited in Plants for a future, 2021). Caper is unsuitable in the reference period and moderate, respectively highly suitable, in the first and second future periods. Suitability is only given under RCP8.5. The high suitability in the future is somewhat surprising, since capers, as frost-sensitive perennials, must be damaged by the frost that will also occur in the future. The variability in the first future period is relatively high, indicating somewhat unstable and alternating growing conditions. Due to the low level of available information, no conclusive statement on the nutritional quality is possible.

Okra

The young fruit of okra is eaten cooked or dried. Okra originates from Western Africa and can today also be found in South Asia and the Americas. The crop grows best on well-drained fertile soils in a sunny position and on slightly acidic soil (Huxley, 1992, as cited in Plants for a future, 2021). Okra is an annual crop that prefers high moisture levels and does not tolerate frost (Rice, 1987, as cited in Plants for a future, 2021). The climatic suitability is only given under RCP8.5 and is very marginal in the reference period. The suitability increases over time but stays moderate, indicating that unabated warming would increase this crop's potential. The relatively low suitability values could be due to the plants' sensitivity to frost and water requirements. The variability between the model chains increases over time and is relatively high in the second future period, indicating an increasing cultivation risk. Due to the low level of available information, no conclusive statement on the nutritional quality is possible.

4.2 Climatic suitability

The results in Table 3 show that the climatic suitability under RCP4.5 increases from period to period for all crops. Under RCP8.5, however, the climatic suitability of 7 crops increases first but decreases in the second future period. Hence unmitigated climate change seems to harm some crops eventually. The total number of potential crops and the climatic suitability are higher under RCP8.5 than under RCP4.5. It should be noted that the climatic suitability is reached under rainfed conditions. When irrigation is sustainable and possible, some crops will have a higher suitability. Table 5 shows the model chain bias for the reference period of the scenarios 4.5 and 8.5 with respect to the historical climate data from MeteoSwiss. It seems like climatic suitability is slightly underestimated under the projected climate data. This finding should be considered when interpreting future suitability values under the two scenarios.

4.3 Regional characteristics and differences

The model was conducted for different stations to trace the model's sensibility and range. The number of crops and their suitability differed from station to station, indicating that the model is indeed sensitive to different locations and conditions. The highest number of crops was obtained in the warm-tempered Lugano and the lowest number of crops in the much cooler Samedan, which lies at 1720 m. These results are somewhat expected as the ecocrop database contains an above-average number of warm-temperate, subtropical, and tropical crops. It is unlikely that a station at this altitude would experience such a strong warming to be a suitable environment for these plants. On the other hand, also well-established crops are included in the database, and one could expect an altitudinal shift in their spatial suitability. Another interesting aspect is that most of the stations had very similar crop compositions. The maps in Figures 9 and 10 show the spatial pattern of climatic suitability in the reference period. The maps were created using the historical data for the reference period, not the projected data from RCP4.5 or RCP8.5. The suitability values for station Zürich that were obtained with the historical data are the same or slightly higher than those obtained with the projected data. This difference points to the bias of the model chains of the projection data and should be kept in mind when discussing the suitability values for the future.

4.4 Potential benefits of the study findings

This work aimed to study prospects of the cultivation of alternative crops and to identify crops that would benefit from future climate changes in Switzerland and complement the crop portfolio. The results show high climatic potential with increasing trends under climate change, where the number and composition of crops depend on the location. For station Zürich, 25 crops were identified, whose potential increases either under RCP4.5 or RCP8.5. The findings suggest that alternative crops' cultivation could be a useful climate adaptation measure, especially at lower altitude sites. As mentioned in chapter 1.4, it is expected that unmitigated climate change will have adverse effects on Swiss agriculture in the long term (OcCC / ProClim, 2007). This can be partially confirmed as the results show decreasing suitability in the second future period under RCP8.5 for several crops. Although the suitability maps were only computed for the reference period (due to time limitations), they come in handy to assess the spatial pattern of a crop's suitability. Farmers could use the maps to see if a crop would be suitable for their site from a climatically perspective. In addition, it would be essential to calculate the maps for the future periods in future works. It would be very interesting to see spatial shifts of suitability and new potential arable areas. A positive aspect of adaptation employing alternative crops is that the demand that is currently met by imports could increasingly be met by local production. This would eliminate long and emission-intensive transport routes (Gardner *et al.*, 2021). The climate-smart agriculture approach aims to reorient agricultural systems to be more resilient and adaptive to climate change (Lipper *et al.*, 2014). Alternative or novel crops present opportunities for climate-smart agriculture and could contribute to agro-ecosystems with low greenhouse gas emissions (Mabhaudhi *et al.*, 2019, and Gardner *et al.*, 2021). For example, sunflowers cause fewer emissions than conventional rapeseed (which they could replace) because they require less nitrogen input and therefore emit less nitrous oxide (N_2O) (Debaeke *et al.*, 2017). Legumes also offer an opportunity, as they fix the required N themselves and emit less N_2O than cropping systems that are fertilised with industrial N (Jensen *et al.*, 2012).

This study examines the possibilities of emerging cultivation potentials for niche crops in Switzerland for the first time. Gardner *et al.* (2021), Abdallah and Jaafar (2019), Ramirez-Villegas *et al.* (2013) and Makinano-Santillan and Santillan (2015) had similar approaches to evaluate the climatic suitability of crops. Gardner *et al.* (2021) aimed to find novel crops adapted to future climatic conditions in parts of Great Britain. The authors selected potential crops by interviewing experts and, similar to this work's approach, used the ecocrop model to compute their climatic suitability. This approach also considered non-climatic factors which would be a valuable addition in future works. Abdallah and Jaafar (2019) used the ecocrop model to assess the future suitability and shifts of the suitability of crops in the Near East and Nile basin. In contrast to this work, no alternative crops were sought here, but the future suitability of major crops was assessed. It would be interesting to compute the future suitability of current major crops in Switzerland as well as this could, for example, point out the need for alternative crops.

A very comprehensive study by Ramirez-Villegas *et al.* (2013) assessed sorghum's future suitability in Africa and Southeast Asia. Contrary to this work, the model was calibrated and validated for sorghum. Current point-based crop presence and high-resolution climate data were used to assess the correct ecological parameters for sorghum statistically. The model performed well, achieving a high true-positive score and correctly represented climatic suitability's spatial distribution. Makinano-Santillan and Santillan (2015), who assessed the future climatic suitability for sago palms in the Philippines, also validated the ecocrop model. The model showed a high prediction rate of 90%. Of course, this is not a substitute for a model validation of the crops identified in this work, but the results by Ramirez-Villegas *et al.* (2013) and Makinano-Santillan and Santillan (2015) give confidence that the crop-specific suitability values from the ecocrop database are accurate.

The cultivation of alternative crops can also be discussed regarding the topic of nutrition. The results show the nutritional value of the selected crops and thus the opportunities they offer. Wormseed and borage are a source of 14 out of 24 nutrients and therefore very nutritious. Since they are consumed as herbs or tea, they do not take up a large part of the daily diet. Especially in the categories of fruits and nuts, and legumes, several crops are a good source of many nutrients, such as common fig, sesame, cranberries, quinoa, lentil, chick pea, yellow lupine, and white lupine. Yellow and white lupine are particularly of interest, as protein-rich legumes could be used as a meat substitute like soy (Heine *et al.*, 2018, and Frick *et al.*, 2002). No crop reaches an INQ of >1 for protein, but yellow lupine reaches 0.91 and white lupine 0.67. As a gluten-free pseudocereal, quinoa could be beneficial for people suffering from gluten intolerance (Jancurová *et al.*, 2009). Several studies show that a plant-based and balanced diet from regional organic sources is healthy and a valuable mitigation measure (Ferrari *et al.*, 2020). 37% of global greenhouse gas emissions are caused by all processes related to the food system (Vicente-Vicente and Piorr, 2021). Pieper *et al.* (2020) calculate the externale climate costs for foods. Assuming a pricing of 180 €/tCO_2-equivalents, legumes, for example, would have to be 33% and poultry 138% more expensive. This illustrates that animal-based products have significantly higher externalised costs than plant-based products. Changing the way we eat, manage and distribute food would significantly reduce emissions from agriculture.

4.5 Limitations

According to CH2018 (2018), the central tendency of a model ensemble (shown in Tables 3 and 4) provides a best-guess estimate and its spread or range gives an indication of uncertainty, which is caused by both model imperfections and natural variability. The variability between the model chains is relatively high in some cases, as for browntop millet, almond or scarlet runner bean. Those crops' suitability values require a critical assessment and provide a higher risk for farmers who seek to grow them. Another interesting aspect is that under RCP4.5, the variability in the first future period is often higher than in the second future period. However, one would expect an increasing deviation from the multi-model mean with time. It is unclear what causes this pattern other than a bias in the model chains for this period and scenario.

The scope of this work does not account for the adaptation to climatic variability. As the frequency and intensity of extreme events in Switzerland is likely to increase in the 21st century, adaptation of the Swiss food production and further research on this topic is necessary (CH2014-Impacts, 2014). With an increasing number of heatwaves, droughts, and extreme precipitation, the production risk increases as well. One strategy of risk prevention is the diversification of farms. The global food system is heavily focused on a few crops: wheat, rice, soya and maize. The food and nutritional security is therefore threatened by extreme events (Gregory *et al.*, 2019). By growing crops with different requirements that are adapted to different conditions, an extreme event will likely not result in total yield and income loss. The successful diversification of the cultivation portfolio and thus the adaptation to climatic fluctuations require more information about Switzerland's alternative crops. The results of this work provide a basis for further research into this adaptation option.

Another limitation is the model's simplicity, as it only considers abiotic parameters (temperature and precipitation). Gardner *et al.* (2021) identify essential aspects that influence farmers decision to grow a novel or alternative crop, other than its climatic suitability. Financial costs play a significant role, special mechanisation or if further processing of the yield is needed. If not enough knowledge about the cultivation is available, this comes with a risk of obtaining only little or no yield. Marketing and sales are essential factors as well, as the availability and size of a niche market matter for a profitable production (Gardner *et al.*, 2021). A further limitation is that the crop-specific thresholds were specified by different experts, hence creating rather heterogeneous data which has not been validated.

Since the model uses mean values as climate data input, it does not account for climatic extremes that occur in shorter periods than a month but might still coincide with critical development stages (Ramirez-Villegas *et al.*, 2013). As climatic variability and short-term extreme events will increase in the future, models with a higher temporal resolution will be needed to account for this source of uncertainty (Gardner *et al.*, 2021). Another uncertainty is the model's sensitivity towards frost days, as even in the second future period under RCP8.5 at very low elevations, it is unlikely that there wont be frost days at all (CH2018, 2018). It is therefore questionable why a perennial, frost-sensitive plant like caper nevertheless has a high climatic suitability under these conditions.

Ramirez-Villegas *et al.* (2013) point out that the ecocrop model is more suitable to be computed over a larger geographical area than for single points. This could be a reason for the slight deviation of the station-based suitability values from the grid-based suitability (in each case for the reference period with the historical data).

Model validation is essential but proves to be difficult as these are alternative crops that are mostly not yet cultivated in Switzerland. The Agroscope and Strickhof field experiments for quinoa, white lupine, and lentil only provide data for one to two years and just a few locations. Model validation would require to validate the climatic suitability via the areas where a crop is currently successfully cultivated, which is difficult when little comparative data is available. However, a rough estimate of the validity of the model results is possible by comparing the successful field trials with the moderate to high suitability values of lentil, quinoa, and white lupine at station Zürich (and for quinoa also at station Changins) (Levy *et al.*, 2019, Strickhof, 2019 and Carrel and Zingg, 2020). Model validation and a higher temporal resolution should be accounted for in-depth in future works.

5 Conclusion

25 alternative crops were identified that are suitable for cultivation under future climate change in Switzerland. Their climatic suitability was evaluated under different scenarios, and their potential was discussed based on characteristics such as their nutritional quality. The lists of crops and their mapped suitability can be used in many ways. They can be the first indication for farmers who want to cultivate alternative crops, and the maps can be used to identify suitable regions to grow them. Another aspect is that the findings can indicate a direction and orientation of future field experiments. The aim and results of this work are in line with the climate smart agriculture approach, which aims to make agricultural systems more resilient and adaptable to climate change. Some of the listed crops are imported into Switzerland today and cause emissions due to the long transport routes. If it would be possible to grow them in Switzerland, those emissions could be avoided. However, this work should be seen as a reminder of the impact a worst-case scenario like RCP8.5 would have on agroecosystems. Growing alternative crops is nevertheless a valuable adaptation method that comes in handy due to the already experienced changes. The next step would be to systematically collect field reports on alternative crops that are already grown in Switzerland and learn more about farmers motivation, obstacles, and needs in this relation. With quantitative data, further models could be fed and validated to make a more detailed statement about climatic suitability under climate change.

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A Appendix

A.1 Categorisation of crops

Table 6: Categorisation of crops (World Program for the Census of Agriculture, 2010)

ID	**Type**
C	Cereals (maize, wheat, rice...)
V	Vegetables (lettuce, onion, herbs. . .)
FN	Fruits and nuts (dates, apples, almonds. . .)
OI	Oilseed crops (soybeans, sesame, olives, coconut, rapeseed. . .)
R	Root/tuber crops with high starch content (potatoes, cassava, yams. . .)
B	Beverage and spice crops (coffee, tea, peppers, ginger. . .)
L	Leguminous crops/Pulses (chickpeas, lupins, beans. . .)
S	Sugar crops (sugar beet, sugar cane. . .)
GF	Grasses, fodders
FI	Fiber (cotton, jute, hemp. . .)
O	Other crops (medical, flowers, rubber, tobacco, trees without anything edible, toxic and addictive plants..)
P	Potential (does not hold for the categories GF,FI & O and other non-edible crops)

A.2 Potential crops for different stations

Zurich (Reckenholz)									
RCP4.5					RCP8.5				
	Crop	REF	FUT1	FUT2		Crop	REF	FUT1	FUT2
1	White Lupine	0.712	0.86	0.904	1	Spinach beet	0.47	0.612	0.595
2	Yellow Lupine	0.595	0.69	0.725	2	English walnut	0.31	0.598	0.662
3	Hairy gooseberry	0.547	0.63	0.658	3	White Lupine	0.71	0.911	0.97
4	Black walnut	0.598	0.69	0.725	4	Yellow Lupine	0.59	0.73	0.803
5	Tarragon	0.688	0.87	0.912	5	Hairy gooseberry	0.55	0.671	0.517
6	Thyme	0.492	0.59	0.612	6	Black currant	0.38	0.581	0.648
7	Dandelion	0.947	0.95	0.974	7	Black walnut	0.6	0.736	0.774
8	Fat hen	0.598	0.7	0.714	8	Corn mint	0.29	0.577	0.779
9	Black mustard	0.854	0.94	0.975	9	Tarragon	0.69	0.974	0.665
10	Licorice, Common	0.947	0.95	0.982	10	Thyme	0.49	0.651	0.675
11	Licorice, American	0.721	0.72	0.698	11	Dandelion	0.94	0.986	0.694
12	Sugar maple	0.522	0.62	0.727	12	Fat hen	0.6	0.713	0.584
13	Heartnut	0.444	0.55	0.63	13	Black mustard	0.85	0.981	0.936
14	Hierochloe odorata	0.734	0.87	0.911	14	Licorice, Common	0.94	0.993	0.953
15	Sugar beet	0.5	0.61	0.685	15	Caper	0	0.665	0.938
16	Wheat, common	0.444	0.59	0.651	16	Sugar maple	0.52	0.743	0.789
17	Barley	0.577	0.7	0.733	17	Heartnut	0.45	0.649	0.686
18	Cabbage	0.926	0.95	0.982	18	Hierochloe odorata	0.73	0.918	0.998
19	Lentil	0.814	0.86	0.94	19	Sugar beet	0.5	0.727	0.808
20	Linseed	0.868	0.93	0.985	20	Wheat, common	0.45	0.697	0.715
21	Garden rocket	0.921	0.94	0.982	21	Swede rap	0.41	0.59	0.704
22	Broad bean	0.632	0.66	0.684	22	Barley	0.58	0.769	0.808
23	Cherry, Sour	0.466	0.56	0.611	23	Oats	0.41	0.636	0.637
24	Black raspberry	0.595	0.6	0.608	24	Cabbage	0.92	0.988	0.934
25	Parsnip	0.932	0.94	0.9	25	Lentil	0.81	0.93	0.947
26	Rutabaga	0.501	0.66	0.724	26	Linseed	0.86	0.981	0.943
27	Seakale	0.738	0.84	0.902	27	Garden rocket	0.91	0.988	0.933
28	Teff	0.618	0.64	0.688	28	Tomato	0.48	0.604	0.576
29	Sweet bay	0.572	0.7	0.744	29	Watermelon	0	0.394	0.693
30	Borage	0.5	0.64	0.685	30	Broad bean	0.63	0.689	0.665
31	Chufa	0.95	0.96	0.982	31	Cherry, Sour	0.47	0.627	0.715
32	Southernwood	0.786	0.97	0.978	32	Black raspberry	0.59	0.613	0.481
33	Sunflower	0.683	0.71	0.739	33	Rutabaga	0.5	0.776	0.858
34	Crowfoot grass	0.413	0.57	0.624	34	Common fig	0.43	0.575	0.67
35	Browntop millet	0.688	0.76	0.907	35	Seakale	0.73	0.914	0.903
36	Wormseed	0.5	0.61	0.673	36	Teff	0.62	0.695	0.692
37	Virginia strawberry	0.497	0.61	0.612	37	Goat chili	0.31	0.625	0.744
38	Chilgoza pine	0.67	0.76	0.742	38	Sweet bay	0.57	0.751	0.84
39	Potato	0.934	0.95	0.985	39	Borage	0.5	0.727	0.623
40	Sesame seed	0.455	0.61	0.686	40	Summer savory	0.08	0.495	0.783
41	Almond	0.002	0.5	0.732	41	Chufa	0.95	0.993	0.956
42	Pecan nut	0.444	0.61	0.653	42	Southernwood	0.79	0.989	0.667
43	Horseradish	0.438	0.62	0.672	43	Sand pear	0.25	0.5	0.618
44	Parsley	0.53	0.68	0.742	44	Okra, lady fingers	0.31	0.594	0.678
45	Cranberry	0.727	0.76	0.867	45	Sunflower	0.68	0.747	0.723
46	Lowbush blueberry	0.738	0.83	0.859	46	Crowfoot grass	0.41	0.634	0.826
47	Shallot	0.711	0.79	0.801	47	Browntop millet	0.68	0.905	0.858

48	Wheat, durum	0.65	0.72	0.759	48	Wormseed	0.5	0.699	0.729
49	Quinoa	0.625	0.74	0.775	49	Virginia strawberry	0.5	0.61	0.399
50	Buffalo gourd	0.636	0.75	0.791	50	Chilgoza pine	0.67	0.731	0.739
51	Rye	0.444	0.61	0.648	51	Chinese boxthorn	0	0.58	0.806
52	Bean, Common	0.683	0.81	0.855	52	Potato	0.93	0.99	0.947
53	Scarlet runner bean	0	0.52	0.74	53	Sesame seed	0.45	0.697	0.847
54	Pumpkin	0.455	0.57	0.653	54	Onion	1	0.999	0.991
55	Hot pepper	0.559	0.64	0.7	55	Almond	0	0.94	1
					56	Pecan nut	0.45	0.7	0.817
					57	Hyacinth bean	0.43	0.6	0.678
					58	Horseradish	0.44	0.734	0.574
					59	Parsley	0.53	0.76	0.574
					60	Cranberry	0.72	0.851	0.865
					61	Lowbush blueberry	0.73	0.853	0.665
					62	Hops	0.21	0.571	0.672
					63	Shallot	0.71	0.849	0.815
					64	Wheat, durum	0.65	0.797	0.869
					65	Quinoa	0.63	0.803	0.682
					66	Buffalo gourd	0.63	0.798	0.926
					67	Rye	0.45	0.697	0.658
					68	Chick pea	0.75	0.763	0.731
					69	Bean, Common	0.68	0.862	0.95
					70	Horse gram	0	0.39	0.634
					71	Scarlet runner bean	0	0.82	0.893
					72	Pumpkin	0.45	0.651	0.682
					73	Pearl millet	0.39	0.536	0.624
					74	Hot pepper	0.56	0.705	0.767

Changins									
RCP4.5					RCP8.5				
	Crop	REF	FUT1	FUT2		Crop	REF	FUT1	FUT2
1	Spinach beet	0.521	0.59	0.634	1	Spinach beet	0.52	0.607	0.514
2	English walnut	0.434	0.57	0.644	2	English walnut	0.44	0.663	0.621
3	White Lupine	0.793	0.9	0.984	3	White Lupine	0.79	0.986	0.857
4	Yellow Lupine	0.636	0.74	0.763	4	Yellow Lupine	0.63	0.771	0.785
5	Black currant	0.456	0.54	0.609	5	Black currant	0.46	0.631	0.592
6	Corn mint	0.443	0.63	0.708	6	Corn mint	0.44	0.744	0.887
7	Tarragon	0.809	0.94	0.898	7	Tarragon	0.81	0.9	0.436
8	Thyme	0.595	0.6	0.622	8	Thyme	0.6	0.61	0.568
9	Caper	0.157	0.69	0.869	9	Garden angelica	0.52	0.505	0.66
10	Sugar maple	0.647	0.7	0.781	10	Caper	0.17	0.985	1
11	Heartnut	0.547	0.6	0.666	11	Sugar maple	0.65	0.782	0.705
12	Hierochloe odorata	0.809	0.95	0.986	12	Heartnut	0.55	0.672	0.624
13	Sugar beet	0.588	0.68	0.756	13	Hierochloe odorata	0.8	0.987	0.996
14	Wheat, common	0.547	0.68	0.738	14	Sugar beet	0.59	0.791	0.744
15	Swede rap	0.473	0.6	0.644	15	Wheat, common	0.55	0.767	0.58
16	Barley	0.652	0.77	0.813	16	Swede rap	0.47	0.654	0.773
17	Oats	0.497	0.64	0.682	17	Barley	0.66	0.848	0.774
18	Lentil	0.863	0.86	0.886	18	Oats	0.5	0.721	0.548
19	Cherry, Sour	0.521	0.61	0.668	19	Lentil	0.86	0.888	0.836

20	Rutabaga	0.608	0.75	0.823	20	Safflower	0.37	0.54	0.621
21	Common fig	0.478	0.58	0.62	21	Cherry, Sour	0.52	0.673	0.66
22	Goat chili	0.434	0.6	0.708	22	Rutabaga	0.61	0.855	0.823
23	Sweet bay	0.626	0.73	0.759	23	Common fig	0.48	0.628	0.728
24	Borage	0.588	0.72	0.757	24	Goat chili	0.44	0.763	0.787
25	Summer savory	0.253	0.52	0.636	25	Sweet bay	0.62	0.758	0.755
26	Southernwood	0.924	0.95	0.898	26	Borage	0.59	0.799	0.421
27	Crowfoot grass	0.502	0.66	0.727	27	Summer savory	0.24	0.625	0.664
28	Drin	0.628	0.76	0.83	28	Kurrel	0.42	0.524	0.602
29	Wormseed	0.588	0.67	0.726	29	Sand pear	0.35	0.61	0.705
30	Chinese boxthorn	0.152	0.6	0.689	30	Crowfoot grass	0.5	0.736	0.833
31	Sesame seed	0.552	0.69	0.762	31	Gum arabic tree	0.15	0.409	0.626
32	Almond	0.236	0.91	0.995	32	Channel millet	0.06	0.442	0.747
33	Pecan nut	0.547	0.7	0.766	33	Drin	0.62	0.805	0.865
34	Hyacinth bean	0.498	0.61	0.644	34	Wormseed	0.59	0.734	0.662
35	Horseradish	0.559	0.71	0.71	35	Little millet	0.06	0.442	0.751
36	Parsley	0.676	0.72	0.705	36	Oca	0	0.332	0.605
37	Hops	0.353	0.58	0.657	37	Chinese boxthorn	0.12	0.708	0.859
38	Wheat, durum	0.694	0.78	0.818	38	Potato, Bitter	0	0.172	0.676
39	Quinoa	0.706	0.77	0.751	39	Sesame seed	0.55	0.728	0.699
40	Buffalo gourd	0.701	0.82	0.866	40	Almond	0.26	0.998	0.954
41	Rye	0.547	0.7	0.732	41	Garden strawberry	0	0.324	0.634
42	Bean, Common	0.737	0.86	0.896	42	Pecan nut	0.55	0.81	0.869
43	Scarlet runner bean	0.28	0.77	0.855	43	Hyacinth bean	0.5	0.673	0.75
44	Hot pepper	0.603	0.66	0.703	44	Wax gourd	0.29	0.508	0.642
					45	Horseradish	0.56	0.724	0.435
					46	Parsley	0.68	0.708	0.435
					47	Hops	0.36	0.723	0.641
					48	Rosemary	0.25	0.51	0.628
					49	Bird rape	0.39	0.545	0.644
					50	Wheat, durum	0.69	0.841	0.664
					51	Quinoa	0.71	0.752	0.617
					52	Buffalo gourd	0.7	0.873	0.882
					53	Rye	0.55	0.76	0.548
					54	Bean, Common	0.74	0.913	0.917
					55	Scarlet runner bean	0.21	0.84	0.817
					56	Hot pepper	0.6	0.687	0.639

Samedan									
RCP4.5					RCP8.5				
	Crop	REF	FUT1	FUT2		Crop	REF	FUT1	FUT2
1	Sea buckthorn	0.47	0.81	0.902	1	Sea buckthorn	0.47	0.928	0.928
2	Mediterranean sal	0.449	0.61	0.644	2	Mediterranean sal	0.45	0.677	0.677

Basel									
RCP4.5					RCP8.5				
	Crop	REF	FUT1	FUT2		Crop	REF	FUT1	FUT2
1	Spinach beet	0.56	0.63	0.70	1	Spinach beet	0.56	0.70	0.70
2	Orchard grass	0.74	0.78	0.79	2	Orchard grass	0.74	0.76	0.76

3	White Lupine	0.80	0.85	0.92	3	White Lupine	0.79	0.90	0.90
4	Yellow Lupine	0.66	0.76	0.78	4	Yellow Lupine	0.66	0.79	0.79
5	Common red ribes	0.70	0.77	0.77	5	Common red ribes	0.70	0.74	0.74
6	Corn mint	0.46	0.56	0.60	6	Corn mint	0.46	0.63	0.63
7	Tarragon	0.82	0.95	0.95	7	Tarragon	0.82	0.95	0.95
8	Dandelion	0.69	0.75	0.72	8	Dandelion	0.68	0.71	0.71
9	Bitter vetch	0.74	0.78	0.79	9	Bitter vetch	0.74	0.76	0.76
10	Black mustard	0.65	0.68	0.68	10	Black mustard	0.65	0.67	0.67
11	Licorice, Common	0.69	0.75	0.72	11	Licorice, Common	0.68	0.71	0.71
12	Caper	0.17	0.67	0.82	12	Caper	0.19	0.96	0.96
13	Hierochloe odorata	0.81	0.93	0.97	13	Hierochloe odorata	0.81	0.98	0.98
14	Swede rap	0.52	0.63	0.67	14	Swede rap	0.52	0.68	0.68
15	Barley	0.66	0.77	0.80	15	Barley	0.66	0.84	0.84
16	Oats	0.50	0.63	0.67	16	Oats	0.51	0.71	0.71
17	Cabbage	0.69	0.72	0.70	17	Lentil	0.58	0.68	0.68
18	Lentil	0.58	0.67	0.68	18	Rutabaga	0.52	0.60	0.60
19	Linseed	0.75	0.75	0.74	19	Common fig	0.52	0.65	0.65
20	Garden rocket	0.69	0.71	0.68	20	Borage	0.60	0.79	0.79
21	Parsnip	0.69	0.73	0.69	21	Burnet	0.71	0.75	0.75
22	Rutabaga	0.52	0.58	0.61	22	Chufa	0.69	0.73	0.73
23	Common fig	0.51	0.61	0.64	23	Southernwood	0.93	0.95	0.95
24	Sweet bay	0.50	0.58	0.61	24	Crowfoot grass	0.50	0.72	0.72
25	Borage	0.59	0.72	0.74	25	Drin	0.80	0.90	0.90
26	Burnet	0.71	0.78	0.78	26	Chilgoza pine	0.61	0.84	0.84
27	Chufa	0.69	0.76	0.73	27	Chinese boxthorn	0.44	0.72	0.72
28	Southernwood	0.92	0.97	0.95	28	Sesame seed	0.51	0.62	0.62
29	Crowfoot grass	0.50	0.65	0.71	29	Almond	0.28	0.83	0.83
30	Drin	0.81	0.88	0.88	30	Pecan nut	0.51	0.68	0.68
31	Garden oarch	0.79	0.78	0.79	31	Hyacinth bean	0.50	0.67	0.67
32	Chilgoza pine	0.62	0.80	0.86	32	Horseradish	0.52	0.68	0.68
33	Chinese boxthorn	0.43	0.64	0.71	33	Hops	0.37	0.70	0.70
34	Potato	0.75	0.76	0.74	34	Wheat, durum	0.50	0.72	0.72
35	Sesame seed	0.52	0.57	0.63	35	Quinoa	0.71	0.77	0.77
36	Almond	0.26	0.77	0.82	36	Buffalo gourd	0.70	0.86	0.86
37	Pecan nut	0.51	0.61	0.67	37	Rye	0.51	0.68	0.68
38	Hyacinth bean	0.50	0.60	0.64	38	Bean, Common	0.74	0.85	0.85
39	Horseradish	0.52	0.64	0.68					
40	Hops	0.36	0.58	0.64					
41	Wheat, durum	0.51	0.67	0.76					
42	Quinoa	0.71	0.78	0.77					
43	Buffalo gourd	0.70	0.80	0.85					
44	Rye	0.51	0.61	0.67					
45	Bean, Common	0.74	0.81	0.87					

Lugano									
RCP4.5					RCP8.5				
	Crop	REF	FUT1	FUT2		Crop	REF	FUT1	FUT2
1	English walnut	0.72	0.89	0.96	1	English walnut	0.72	0.98	0.98
2	White Lupine	0.98	0.98	0.95	2	Yellow Lupine	0.80	0.88	0.88
3	Yellow Lupine	0.80	0.90	0.89	3	Chestnut, European	0.72	0.93	0.93

4	Chestnut, European	0.72	0.83	0.90
5	Quarkgrass	0.83	0.85	0.85
6	Corn mint	0.74	0.90	0.90
7	Spearmint	0.72	0.74	0.75
8	Thyme	0.96	1.00	1.00
9	Bitter vetch	0.65	0.66	0.64
10	Garden angelica	0.71	0.90	0.96
11	Caper	0.84	0.91	0.89
12	Sugar maple	0.87	0.95	0.89
13	Wheat, common	0.53	0.61	0.55
14	Swede rap	0.68	0.79	0.81
15	Barley	0.77	0.78	0.76
16	Lentil	0.93	0.98	0.97
17	Linseed	0.73	0.85	0.83
18	Garden rocket	0.78	0.97	0.93
19	Tomato	0.82	0.96	0.99
20	Groundnut	0.64	0.79	0.83
21	Watermelon	0.54	0.86	0.86
22	Squash gourd	0.79	0.95	0.99
23	Broad bean	0.98	0.99	0.99
24	Apricot	0.67	0.75	0.76
25	Plum	0.56	0.66	0.72
26	European hazelnut	0.63	0.74	0.79
27	Sodum apple	0.77	0.91	0.96
28	Cherry, Sour	0.71	0.81	0.85
29	Rutabaga	0.67	0.78	0.74
30	Winter squash	0.46	0.67	0.75
31	Common fig	0.65	0.74	0.78
32	Seakale	0.73	0.86	0.79
33	Teff	0.79	0.87	0.90
34	Pimentchien	0.54	0.89	0.97
35	Goat chili	0.72	0.88	0.90
36	Basil	0.52	0.58	0.65
37	Sweet bay	0.84	0.96	0.94
38	Clary sage	0.53	0.60	0.71
39	Summer savory	0.62	0.85	0.80
40	Custard banana	0.83	0.83	0.83
41	Giant hazelnut	0.52	0.61	0.61
42	Sand pear	0.57	0.72	0.75
43	Turkish hazel	0.56	0.66	0.67
44	Soyabean	0.77	0.94	0.99
45	Okra, lady fingers	0.72	0.93	0.98
46	Sisal	0.35	0.59	0.68
47	Hausa groundnut	0.95	1.00	1.00
48	Sword bean	0.24	0.71	0.89
49	Crowfoot grass	0.70	0.86	0.91
50	Gum arabic tree	0.37	0.55	0.60
51	Japanese millet	0.66	0.75	0.74
52	Channel millet	0.39	0.64	0.67
53	Black cumin	0.62	0.84	0.79

4	Quarkgrass	0.83	0.86	0.86
5	Corn mint	0.74	0.91	0.91
6	Spearmint	0.73	0.74	0.74
7	Thyme	0.96	0.99	0.99
8	Bitter vetch	0.64	0.67	0.67
9	Garden angelica	0.71	0.97	0.97
10	Licorice, Common	1.00	1.00	1.00
11	Caper	0.84	0.88	0.88
12	Sugar maple	0.88	0.90	0.90
13	Swede rap	0.68	0.82	0.82
14	Lentil	0.93	0.96	0.96
15	Linseed	0.73	0.85	0.85
16	Garden rocket	0.76	0.96	0.96
17	Tomato	0.82	0.99	0.99
18	Groundnut	0.64	0.84	0.84
19	Watermelon	0.54	0.86	0.86
20	Squash gourd	0.79	0.99	0.99
21	Broad bean	0.98	0.99	0.99
22	Apricot	0.66	0.73	0.73
23	Plum	0.56	0.72	0.72
24	European hazelnut	0.62	0.76	0.76
25	Sodum apple	0.77	0.95	0.95
26	Cherry, Sour	0.71	0.86	0.86
27	Rutabaga	0.67	0.73	0.73
28	Winter squash	0.46	0.78	0.78
29	Common fig	0.65	0.79	0.79
30	Seakale	0.72	0.74	0.74
31	Teff	0.78	0.91	0.91
32	Pimentchien	0.54	0.97	0.97
33	Goat chili	0.72	0.92	0.92
34	Basil	0.52	0.67	0.67
35	Sweet bay	0.84	0.93	0.93
36	Clary sage	0.53	0.71	0.71
37	Summer savory	0.61	0.79	0.79
38	Chufa	1.00	1.00	1.00
39	Giant hazelnut	0.52	0.66	0.66
40	Sand pear	0.58	0.74	0.74
41	Turkish hazel	0.55	0.63	0.63
42	Soyabean	0.77	0.99	0.99
43	Okra, lady fingers	0.71	0.98	0.98
44	Sisal	0.36	0.70	0.70
45	Hausa groundnut	0.95	1.00	1.00
46	Sword bean	0.26	0.96	0.96
47	Crowfoot grass	0.70	0.92	0.92
48	Gum arabic tree	0.37	0.61	0.61
49	Browntop millet	0.21	0.62	0.62
50	Japanese millet	0.65	0.77	0.77
51	Channel millet	0.38	0.67	0.67
52	Black cumin	0.60	0.81	0.81
53	Mediterranean sal	0.89	0.97	0.97

54	Mediterranean sal	0.90	0.97	0.95
55	Garden oarch	0.87	0.94	0.91
56	Livingstone potato	0.55	0.81	0.81
57	Oca	0.36	0.62	0.68
58	Chinese boxthorn	0.75	0.96	1.00
59	Potato, Bitter	0.15	0.61	0.73
60	Potato	0.87	0.94	0.94
61	Sesame seed	0.77	0.94	0.98
62	Onion	0.87	0.91	0.90
63	Amaranthus	0.48	0.59	0.64
64	Pecan nut	0.77	0.92	0.94
65	Hyacinth bean	0.65	0.75	0.78
66	Wax gourd	0.48	0.62	0.67
67	Peppermint	0.66	0.65	0.68
68	Cranberry	0.72	0.83	0.75
69	European gooseberry	0.81	0.85	0.91
70	Rosemary	0.47	0.62	0.67
71	Shallot	0.63	0.78	0.75
72	Bird rape	0.56	0.66	0.70
73	Cowpea	0.56	0.69	0.73
74	Bean, Common	0.95	1.00	1.00
75	Cluster bean	0.51	0.63	0.67
76	Horse gram	0.54	0.89	0.97
77	Scarlet runner bean	0.96	1.00	1.00
78	Choyote	0.51	0.66	0.73
79	Pumpkin	0.77	0.94	0.99
80	Pearl millet	0.61	0.71	0.72
81	Italian millet	0.99	0.99	0.99
82	Hot pepper	0.78	0.90	0.93
83	Dent maize	0.72	0.93	0.98
84	Flint maize	0.97	1.00	1.00
85	Soft maize	0.72	0.93	0.98
86	Pop maize	0.72	0.93	0.98

54	Garden oarch	0.87	0.92	0.92
55	Livingstone potato	0.55	0.79	0.79
56	Oca	0.36	0.72	0.72
57	Chinese boxthorn	0.76	1.00	1.00
58	Potato, Bitter	0.14	0.72	0.72
59	Potato	0.87	0.96	0.96
60	Sesame seed	0.77	0.99	0.99
61	Onion	0.87	0.89	0.89
62	Amaranthus	0.48	0.66	0.66
63	Pecan nut	0.78	0.95	0.95
64	Hyacinth bean	0.65	0.81	0.81
65	Wax gourd	0.47	0.68	0.68
66	Cranberry	0.71	0.72	0.72
67	European gooseberry	0.81	0.93	0.93
68	Rosemary	0.48	0.71	0.71
69	Shallot	0.62	0.74	0.74
70	Bird rape	0.56	0.71	0.71
71	Cowpea	0.55	0.74	0.74
72	Chick pea	1.00	1.00	1.00
73	Bean, Common	0.95	1.00	1.00
74	Cluster bean	0.51	0.68	0.68
75	Horse gram	0.54	0.97	0.97
76	Scarlet runner bean	0.97	1.00	1.00
77	Tepary bean	0.98	0.99	0.99
78	Choyote	0.51	0.69	0.69
79	Pumpkin	0.77	0.99	0.99
80	Pearl millet	0.61	0.75	0.75
81	Italian millet	0.98	0.99	0.99
82	Hot pepper	0.78	0.94	0.94
83	Dent maize	0.71	0.98	0.98
84	Flint maize	0.96	1.00	1.00
85	Soft maize	0.71	0.98	0.98
86	Pop maize	0.71	0.98	0.98

A.3 Share of highly suitable crops per station

Table 7: Share of highly suitable crops per station

station	scenario	crops >0.8 (in at least one period)	number of total crops	% of highly suitable crops
Zurich	RCP4.5	20	55	**36**
	RCP8.5	35	74	**47**
Changins	RCP4.5	14	44	**31**
	RCP8.5	19	56	**34**
Samedan	RCP4.5	1	2	**50**
	RCP8.5	1	2	**50**
Basel	RCP4.5	11	45	**24**
	RCP8.5	11	38	**29**
Lugano	RCP4.5	64	86	**74**
	RCP8.5	53	86	**62**

A.4 Nutrients for which the crops are respectively a good source

Table 8: INQ values for all crops. Green cells indiacte an INQ >1 (the crop is a good source for that nutrient) INQ= Index of Nutritional Quality. RDA= Recommended Daily Allowances.

Nutrients	Unit	RDA/1000kcal (for women)	Wormseed	Borage	Black mustard	Hot pepper	Teff	Browntop millet	Durum wheat	Quinoa	Almond	Pecan nut	Goji
Fat, total	g	350		0.10	0.14	0.06		0.02	0.01	0.04	0.24	0.30	0.00
Carbohydrates, available	g	500	0.47	0.29	0.20	0.17	0.39	0.42	0.40	0.34	0.01	0.04	0.44
Dietary fibres	g	13.64	8.71		1.83	10.68	2.03	1.78	0.71	1.31	1.61	1.02	2.73
Protein	g	150	0.07	0.57	0.67	0.29	0.22	0.18	0.23	0.27	0.29	0.09	0.27
Vitamin A activity, RE	µg-RE	360	0.12	27.78					0.02	0.01	0.00		
Beta-carotene (mcg)	µg	1200	0.99			3.64	0.01		0.02	0.02	0.00		
Vitamin B1 (thiamine)	mg	0.48	1.82	5.95			2.12		0.41	2.32	0.67		
Vitamin B2 (riboflavin)	mg	0.48	22.66	24.80			1.47		0.35	1.81	1.55		
Vitamin B6 (pyridoxine)	mg	0.55	8.64	7.27			2.29		0.41	2.08	0.46		
Vitamin B12 (cobalamin)	µg	1.6							0.00	0.00	0.00		
Niacin	mg	5.45	3.66	7.86			1.61		1.12	0.22	0.65		
Folate	µg	136.36	49.27	4.54					1.18	2.28	0.59		
Vitamin C (ascorbic acid)	mg	43.18	2.61	38.60		96.29			0.00	0.03	0.00	0.04	3.21
Vitamin D (calciferol)	µg	7.95							0.00	0.00	0.00		
Vitamin E activity	mg-ATE	5.45							0.05	1.99	9.16		
Potassium (K)	mg	1818.18	8.08	12.31	0.83	3.69	0.61	0.10	0.23	1.20	0.70	0.33	
Sodium (Na)	mg	681.82	3.67	5.59			0.05	0.03	0.00	0.04	0.00		1.25
Chloride (Cl)	mg	1045.5							0.24	0.29	0.06		
Calcium (Ca)	mg	454.55	18.91	9.74	1.10		0.74	0.18	0.11	0.48	1.00	0.22	1.20
Magnesium (Mg)	mg	138.64	27.27	17.86		3.04	3.47	2.02	0.55	5.49	2.92	1.26	
Phosphorus (P)	mg	318.18	8.45	7.93			3.52	2.57	0.89	2.82	2.70	1.26	
Iron (Fe)	mg	6.62	8.87	23.74	2.72	1.62	4.53	3.45	0.39	3.28	1.22	0.55	2.94
Iodide (I)	µg	68.18							0.21	0.06	0.05		
Zinc (Zn)	mg	3.18	10.81	2.99		1.71	2.98	2.33	1.96	2.14	3.18	2.06	
sum of values >1			14	14	3	7	9	5	3	11	8	4	5
% of available information			0.75	0.71	0.29	0.46	0.67	0.46	1.00	1.00	1.00	0.46	0.33

Black walnut	Cranberry	Sesame	Common fig	Lentil	White lupine	Yellow lupine	Chick pea	Scarlet runner bean	Sunflower	Chufa	Sugar maple	Okra	Caper
0.27	0.04	0.24	0.01	0.01	0.08	0.05		0.05	0.32	0.17	0.00		
0.03	0.36	0.04	0.42	0.28	0.08	0.03	0.27	0.29		0.21	0.51	0.48	0.40
0.81	5.32	1.44	2.97	3.85	7.24	8.65	3.48	6.66		3.12		8.80	
0.26	0.05	0.23	0.08	0.50	0.67	0.91	0.38	0.48		0.10	0.00	0.54	0.67
	0.14	0.00	0.30	0.03			0.22						
	0.19	0.01	0.45	0.05	0.00	0.21	0.40						
	1.04	2.39	1.41	3.41	2.60	2.78	3.31				0.05		
	1.04	0.31	1.69	0.84	1.40	1.67	0.83				0.08		
	0.45	1.21	2.70	1.29	1.16	2.36	1.83				0.02		
	0.00	0.00	0.00	0.00	0.00	0.00	0.00						
	0.46	1.77	1.24	1.42	1.62	1.53	0.95				0.02		
	0.55	1.40	0.69	3.40	8.05	9.04	7.63						
0.06	6.95	0.00	1.56	0.49			0.36			1.52		16.75	2.81
	0.00	0.00	0.00	0.00			0.00						
	4.54	0.51	1.24	0.16			1.07		11.72	121.38			
0.46	0.96	0.46	1.71	1.46	1.60	2.11	1.83		0.00	0.75	0.43		
0.00	0.07	0.02	0.06	0.01	0.05	0.04	0.04		0.00			0.29	34.09
	0.10	0.02	0.23	0.25			0.23		0.00	0.36			
0.22	0.77	3.44	1.78	0.39	1.18		0.81		0.00	0.10	0.56	5.28	22.20
2.34	1.08	3.95	1.75	2.14	3.56	6.73	3.09			1.89	0.39		
2.60	0.79	2.98	0.98	3.88	3.57	7.61	3.65			2.18	0.03		
0.76	1.89	2.16	1.63	3.73	2.16	4.33	2.49		0.02	3.05	0.69	4.38	5.49
	1.83	0.24	0.30	0.03			0.03						
1.71	1.57	4.44	0.85	3.49	4.95	7.34	2.31				5.38		
3	10	10	12	10	12	10	10	1	1	6	1	4	4
0.50	1.00	1.00	1.00	1.00	0.75	0.71	1.00	0.17	0.29	0.50	0.54	0.29	0.25

A.5 Script to apply the ecocrop model to 651 crops

```
###############################################################################################################
# This script reads in climate data from Zurich Reckenholz and applies the ecocrop model to all 603 selected crops and retrieves #
# a list of crops that match certain criteria (for both scenarios and 3 periods). This script can be used for any other station #
###############################################################################################################

#setwd("~/projects/Malve_Heinz")
#setwd("~/mnt/Data-Work-RE/27_Natural_Resources-
RE/271_KLIM_Work/CC_Impacts/Grundlagen/Master_Arbeiten/Msc_Heinz/R_modeling")
DATAdir<-"~/mnt/Data-Work-RE/27_Natural_Resources-
RE/271_KLIM_Work/CC_Impacts/Grundlagen/Master_Arbeiten/Msc_Heinz/R_modeling/"

### prerequesits
library(dismo)
library(xlsx)
library(data.table)
library(lubridate)
library(dplyr)
library(xts)
library(RiverLoad)
library(magicfor)
library(matrixStats)

################################################################################
### read in climate data (line 24 until line 108)

station = "REH" #stations-Kürzel

scenarios = c("CLMCOM-CCLM4_HADGEM_EUR11_RCP45","CLMCOM-CCLM4_HADGEM_EUR11_RCP85",
        "CLMCOM-CCLM4_ECEARTH_EUR11_RCP45","CLMCOM-CCLM4_ECEARTH_EUR11_RCP85",
        "CLMCOM-CCLM4_MPIESM_EUR11_RCP45","CLMCOM-CCLM4_MPIESM_EUR11_RCP85",
        "MPICSC-REMO1_MPIESM_EUR11_RCP45","MPICSC-REMO1_MPIESM_EUR11_RCP85",
        "MPICSC-REMO2_MPIESM_EUR11_RCP45","MPICSC-REMO2_MPIESM_EUR11_RCP85",
        "SMHI-RCA_ECEARTH_EUR11_RCP45","SMHI-RCA_ECEARTH_EUR11_RCP85",
        "SMHI-RCA_HADGEM_EUR11_RCP45","SMHI-RCA_HADGEM_EUR11_RCP85",
        "SMHI-RCA_IPSL_EUR11_RCP45","SMHI-RCA_IPSL_EUR11_RCP85",
        "DMI-HIRHAM_ECEARTH_EUR11_RCP45","DMI-HIRHAM_ECEARTH_EUR11_RCP85",
        "SMHI-RCA_MPIESM_EUR11_RCP45","SMHI-RCA_MPIESM_EUR11_RCP85")

source("~/mnt/Data-Work-RE/27_Natural_Resources-
RE/271_KLIM_Work/CC_Impacts/Grundlagen/Master_Arbeiten/Msc_Heinz/R_modeling/ET0_penman_monteith.r")
source("~/mnt/Data-Work-RE/27_Natural_Resources-
RE/271_KLIM_Work/CC_Impacts/Grundlagen/Master_Arbeiten/Msc_Heinz/R_modeling/ET0_priestley_taylor.r")
source("~/mnt/Data-Work-RE/27_Natural_Resources-
RE/271_KLIM_Work/CC_Impacts/Grundlagen/Master_Arbeiten/Msc_Heinz/R_modeling/date2doy.r")

for(sc in 1:length(scenarios)){

  z_tasmin <- paste("~/mnt/Data-Raw-RE/27_Natural_Resources-
RE/271_KLIM_Data/CH2018_ClimateProjections/QMstations/tasmin/CH2018_tasmin_",scenarios[sc], "_QMstations_1981-
2099_csv.zip", sep="")
  z_tas <-    paste("~/mnt/Data-Raw-RE/27_Natural_Resources-
RE/271_KLIM_Data/CH2018_ClimateProjections/QMstations/tas/CH2018_tas_",scenarios[sc], "_QMstations_1981-2099_csv.zip",
sep="")
  z_pr <-     paste("~/mnt/Data-Raw-RE/27_Natural_Resources-
RE/271_KLIM_Data/CH2018_ClimateProjections/QMstations/pr/CH2018_pr_",scenarios[sc], "_QMstations_1981-2099_csv.zip",
sep="")

  tmin <- read.csv(unz(z_tasmin, paste("CH2018_tasmin_", scenarios[sc], "_QMstations_1981-2099_", station, ".csv", sep="")),
skip=17, header = TRUE, sep=";")
  tas <- read.csv(unz(z_tas, paste("CH2018_tas_", scenarios[sc], "_QMstations_1981-2099_", station, ".csv", sep="")), skip=17,
header = TRUE, sep=";")
  precip<- read.csv(unz(z_pr, paste("CH2018_pr_", scenarios[sc], "_QMstations_1981-2099_", station, ".csv", sep="")), skip=17,
header = TRUE, sep=";")

  tmin[,2] <- as.numeric(as.character(tmin[,2]))
  tas[,2] <- as.numeric(as.character(tas[,2]))
  precip[,2] <- as.numeric(as.character(precip[,2]))

  y <- tmin$DATE
  mo <- strftime(y, "%m")
  yr <- strftime(y, "%Y")
  tmin <- tmin$VALUE
  tmin <- data.frame(mo, yr, tmin)

 ##flag and fill data gaps:
 for(i in 1:length(tmin [,1])){
   if(is.na(tmin[i,2]) & (i < length(tmin[,1])-4)){
     print(paste("missing value in tmin on day", tmin[i,1], scenarios[sc]))
     tmin[i,2] <- mean(tmin[(i-4):(i+4),2], na.rm=TRUE)
   }else if(is.na(tmin[i,2]) & (i >= length(tmin [,1])-4)){
     print(paste("missing value in tmin on day", tmin[i,1], scenarios[sc]))
     tmin[i,2] <- mean(tmin[(i-4):(i),2], na.rm=TRUE)
   }
   if(is.na(tas[i,2]) & (i < length(tas[,1])-4)){
     print(paste("missing value in tas on day", tas[i,1], scenarios[sc]))
     tas[i,2] <- mean(tas[(i-4):(i+4),2], na.rm=TRUE)
   }else if(is.na(tas[i,2]) & (i >= length(tas[,1])-4)){
     print(paste("missing value in tas on day", tas[i,1], scenarios[sc]))
     tas[i,2] <- mean(tas[(i-4):(i),2], na.rm=TRUE)
   }
   if(is.na(precip[i,2]) & (i < length(precip[,1])-4)){
     print(paste("missing value in precip on day", precip[i,1], scenarios[sc]))
     precip[i,2] <- mean(precip[(i-4):(i+4),2], na.rm=TRUE)
   }else if(is.na(precip[i,2]) & (i >= length(precip [,1])-4)){
     print(paste("missing value in precip on day", precip[i,1], scenarios[sc]))
     precip[i,2] <- mean(precip[(i-4):(i),2], na.rm=TRUE)
   }
 }
 #get DOY and Year:
 year <- matrix(0, nrow = length(tmin[,1]), ncol = 1)
 DOY <- matrix(NA, nrow = length(tmin[,1]), ncol = 1)
 for (j in 1:length(tmin[,1])){
   year[j] <- as.numeric(substr(as.character(tmin[j,2]),1,4))
   month <- as.numeric(substr(as.character(tmin[j,1]),6,7))
   day <- as.numeric(substr(as.character(tmin[j,1]),9,10))

   if((year[j]%%4) == 0){
     DOY[j] <- date2DOY_leap(day, month)
   } else {
     DOY[j] <- date2DOY_perpetual(day, month)
   }
 }
 #write data to text file:

 noDATA <- matrix(NA, nrow = length(tmin[,1]), ncol = 1)
 dat <- cbind(tmin[1], tmin[2],tmin[3],tas[,2], precip[,2])
 colnames(dat) <- c("month", "year","tmin", "tas", "precip" )
 dat_file <- paste(DATAdir, station, "_",scenarios[sc],".csv", sep=";")
 write.table(dat, dat_file,col.names = T, row.names=F, sep=";")
}

################################################################################

### calculating the model for different periods and scenarios


# 1981-2011=REF =     0:10957  ->                          nrows=10957
# 2040-2070=FUT1= 21550:32507  -> 32507-21550->  skip= 21549, nrows=10957
# 2070:2100=FUT2= 32508:43464  -> 43464-32508->  skip= 32507, nrows=10956

################# getting the suitability values for 8.5 #####################


############################### REF period ###############################

# loading in the data files i just saved to my working directory

chain_85_1<-read.csv(";REH;_;CLMCOM-CCLM4_ECEARTH_EUR11_RCP85;.csv", sep=";", nrows = 10957)
chain_85_2<-read.csv(";REH;_;CLMCOM-CCLM4_HADGEM_EUR11_RCP85;.csv", sep=";", nrows = 10957)
chain_85_3<-read.csv(";REH;_;CLMCOM-CCLM4_MPIESM_EUR11_RCP85;.csv", sep=";", nrows = 10957)
chain_85_4<-read.csv(";REH;_;DMI-HIRHAM_ECEARTH_EUR11_RCP85;.csv", sep = ";", nrows = 10957)
chain_85_5<-read.csv(";REH;_;MPICSC-REMO1_MPIESM_EUR11_RCP85;.csv", sep = ";", nrows = 10957)
chain_85_6<-read.csv(";REH;_;MPICSC-REMO2_MPIESM_EUR11_RCP85;.csv", sep = ";", nrows = 10957)
chain_85_7<-read.csv(";REH;_;SMHI-RCA_ECEARTH_EUR11_RCP85;.csv", sep = ";", nrows = 10957)
chain_85_8<-read.csv(";REH;_;SMHI-RCA_HADGEM_EUR11_RCP85;.csv", sep = ";", nrows = 10957)
chain_85_9<-read.csv(";REH;_;SMHI-RCA_IPSL_EUR11_RCP85;.csv", sep = ";", nrows = 10957)
chain_85_10<-read.csv(";REH;_;SMHI-RCA_MPIESM_EUR11_RCP85;.csv", sep = ";", nrows = 10957)
```

```
chains<-
list(chain_85_1,chain_85_2,chain_85_3,chain_85_4,chain_85_5,chain_85_6,chain_85_7,chain_85_8,chain_85_9,chain_85_10)

tmin_agg_REF<- data.frame(NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col =
rep(NA, 12),NA_col = rep(NA, 12)
                  ,NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12))

tas_agg_REF<- data.frame(NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col =
rep(NA, 12),NA_col = rep(NA, 12)
                  ,NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12))

prec_agg_REF<-data.frame(NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col =
rep(NA, 12),NA_col = rep(NA, 12)
                  ,NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12))

for(i in 1:length(chains)){
 tmin_agg<- aggregate(chains[[i]]$tmin ~ chains[[i]]$month, chains[[i]], FUN= mean)
 tmin_agg <- as.vector(tmin_agg[,2])
 tmin_agg_REF[,i]<- tmin_agg
 colnames(tmin_agg_REF)[i]<- paste0("tmin_agg", i)

 tas_agg <- aggregate(chains[[i]]$tas ~ chains[[i]]$month, chains[[i]], FUN= mean)
 tas_agg<- as.vector(tas_agg[,2])
 tas_agg_REF[,i]<-tas_agg
 colnames(tas_agg_REF)[i]<- paste0("tas_agg", i)

 prec_agg<- aggregate(chains[[i]]$precip ~ chains[[i]]$month, chains[[i]], FUN= sum)
 prec_agg<- prec_agg/30
 prec_agg<- as.vector(prec_agg[,2])
 prec_agg_REF[,i]<-prec_agg
 colnames(prec_agg_REF)[i]<- paste0("prec_agg", i)
}

tmin_agg_REF<-as.list(as.data.frame(tmin_agg_REF))
tas_agg_REF<- as.list(as.data.frame(tas_agg_REF))
prec_agg_REF<-as.list(as.data.frame(prec_agg_REF))

for(j in 1:length(tmin_agg_REF)){
 x<-as.vector(tmin_agg_REF[[j]])
 assign(paste0("tmin_agg_REF_",j), x)
}

for(k in 1:length(tas_agg_REF)){
 y<-as.vector(tas_agg_REF[[k]])
 assign(paste0("tas_agg_REF_",k), y)
}

for(l in 1:length(prec_agg_REF)){
 z<-as.vector(prec_agg_REF[[l]])
 assign(paste0("prec_agg_REF_",l), z)
}

##########################################################################

pot_crops<-read.csv("subsetofallcrops_cor.csv", sep=";", na="TRUE")

Crops<-(pot_crops$NAME)
Crops<-as.vector(Crops)

list_tmin85<-
list(tmin_agg_REF_1,tmin_agg_REF_2,tmin_agg_REF_3,tmin_agg_REF_4,tmin_agg_REF_5,tmin_agg_REF_6,tmin_agg_REF_7,
tmin_agg_REF_8,tmin_agg_REF_9,tmin_agg_REF_10)
list_tas85<-
list(tas_agg_REF_1,tas_agg_REF_2,tas_agg_REF_3,tas_agg_REF_4,tas_agg_REF_5,tas_agg_REF_6,tas_agg_REF_7,tas_agg
_REF_8,tas_agg_REF_9,tas_agg_REF_10)
list_prec85<-
list(prec_agg_REF_1,prec_agg_REF_2,prec_agg_REF_3,prec_agg_REF_4,prec_agg_REF_5,prec_agg_REF_6,prec_agg_REF_7
,prec_agg_REF_8,prec_agg_REF_9,prec_agg_REF_10)

REF_85_maxsuit<-matrix(NA,nrow=length(Crops), ncol=length(list_tmin85))
rownames(REF_85_maxsuit)<-Crops

for(i in 1:length(Crops)){
 for(j in 1:10){
   Result<-(ecocrop(crop=Crops[i], list_tmin85[[j]],list_tas85[[j]] ,list_prec85[[j]] , rainfed=TRUE))
   maxsuit<-as.vector(Result@maxsuit)
   REF_85_maxsuit[i,j]<-maxsuit
 }
}

REF_85_maxsuit<-as.data.frame(REF_85_maxsuit)
test<-as.matrix(REF_85_maxsuit)
test2<-rowSds(test, cols = 1:10)
mittel<-rowMeans(REF_85_maxsuit)
mittel<-as.vector(mittel)
REF_85_maxsuit$mean<-mittel
REF_85_maxsuit$sd<-test2

############################ FUT1 Period ################################
#21550:32507  -> 32507-21550= nrows=10957

F1chain_85_1<-read.csv(";REH;_;CLMCOM-CCLM4_ECEARTH_EUR11_RCP85;.csv", sep=";", skip=21549, nrows = 10957)
colnames(F1chain_85_1) = c("month","year","tmin","tas","precip")
F1chain_85_2<-read.csv(";REH;_;CLMCOM-CCLM4_HADGEM_EUR11_RCP85;.csv", sep=";", skip= 21549, nrows = 10957)
colnames(F1chain_85_2) = c("month","year","tmin","tas","precip")
F1chain_85_3<-read.csv(";REH;_;CLMCOM-CCLM4_MPIESM_EUR11_RCP85;.csv", sep=";",  skip= 21549, nrows = 10957)
colnames(F1chain_85_3) = c("month","year","tmin","tas","precip")
F1chain_85_4<-read.csv(";REH;_;DMI-HIRHAM_ECEARTH_EUR11_RCP85;.csv", sep = ";", skip= 21549, nrows = 10957)
colnames(F1chain_85_4) = c("month","year","tmin","tas","precip")
F1chain_85_5<-read.csv(";REH;_;MPICSC-REMO1_MPIESM_EUR11_RCP85;.csv", sep = ";",skip= 21549, nrows = 10957)
colnames(F1chain_85_5) = c("month","year","tmin","tas","precip")
F1chain_85_6<-read.csv(";REH;_;MPICSC-REMO2_MPIESM_EUR11_RCP85;.csv", sep = ";", skip= 21549, nrows = 10957)
colnames(F1chain_85_6) = c("month","year","tmin","tas","precip")
F1chain_85_7<-read.csv(";REH;_;SMHI-RCA_ECEARTH_EUR11_RCP85;.csv", sep = ";", skip= 21549, nrows = 10957)
colnames(F1chain_85_7) = c("month","year","tmin","tas","precip")
F1chain_85_8<-read.csv(";REH;_;SMHI-RCA_HADGEM_EUR11_RCP85;.csv", sep = ";", skip= 21549, nrows = 10957)
colnames(F1chain_85_8) = c("month","year","tmin","tas","precip")
F1chain_85_9<-read.csv(";REH;_;SMHI-RCA_IPSL_EUR11_RCP85;.csv", sep = ";", skip= 21549, nrows = 10957)
colnames(F1chain_85_9) = c("month","year","tmin","tas","precip")
F1chain_85_10<-read.csv(";REH;_;SMHI-RCA_MPIESM_EUR11_RCP85;.csv", sep = ";", skip= 21549, nrows = 10957)
colnames(F1chain_85_10) = c("month","year","tmin","tas","precip")

chains<-
list(F1chain_85_1,F1chain_85_2,F1chain_85_3,F1chain_85_4,F1chain_85_5,F1chain_85_6,F1chain_85_7,F1chain_85_8,F1chain
_85_9,F1chain_85_10)

tmin_agg_F1<- data.frame(NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col =
rep(NA, 12),NA_col = rep(NA, 12)
                  ,NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12))

tas_agg_F1<- data.frame(NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col =
rep(NA, 12),NA_col = rep(NA, 12)
                  ,NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12))

prec_agg_F1<-data.frame(NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col =
rep(NA, 12),NA_col = rep(NA, 12)
                  ,NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12))

for(i in 1:length(chains)){
 tmin_agg<- aggregate(chains[[i]]$tmin ~ chains[[i]]$month, chains[[i]], FUN= mean)
 tmin_agg <- as.vector(tmin_agg[,2])
 tmin_agg_F1[,i]<- tmin_agg
 colnames(tmin_agg_F1)[i]<- paste0("tmin_agg_F1", i)

 tas_agg <- aggregate(chains[[i]]$tas ~ chains[[i]]$month, chains[[i]], FUN= mean)
 tas_agg<- as.vector(tas_agg[,2])
 tas_agg_F1[,i]<-tas_agg
 colnames(tas_agg_F1)[i]<- paste0("tas_agg_F1", i)

 prec_agg<- aggregate(chains[[i]]$precip ~ chains[[i]]$month, chains[[i]], FUN= sum)
 prec_agg<- prec_agg/30
 prec_agg<- as.vector(prec_agg[,2])
 prec_agg_F1[,i]<-prec_agg
 colnames(prec_agg_F1)[i]<- paste0("prec_agg_F1", i)
}

tmin_agg_F1<-as.list(as.data.frame(tmin_agg_F1))
tas_agg_F1<- as.list(as.data.frame(tas_agg_F1))
```

```
prec_agg_F1<-as.list(as.data.frame(prec_agg_F1))

for(j in 1:length(tmin_agg_F1)){
  x<-as.vector(tmin_agg_F1[[j]])
  assign(paste0("tmin_agg_F1_",j), x)
}

for(k in 1:length(tas_agg_F1)){
  y<-as.vector(tas_agg_F1[[k]])
  assign(paste0("tas_agg_F1_",k), y)
}

for(l in 1:length(prec_agg_F1)){
  z<-as.vector(prec_agg_F1[[l]])
  assign(paste0("prec_agg_F1_",l), z)
}
##########################################################################

pot_crops<-read.csv("subsetofallcrops_cor.csv", sep=";", na="TRUE")

Crops<-(pot_crops$NAME)
Crops<-as.vector(Crops)

list_tmin85f1<-
list(tmin_agg_F1_1,tmin_agg_F1_2,tmin_agg_F1_3,tmin_agg_F1_4,tmin_agg_F1_5,tmin_agg_F1_6,tmin_agg_F1_7,tmin_agg_F1
_8,tmin_agg_F1_9,tmin_agg_F1_10)
list_tas85f1<-
list(tas_agg_F1_1,tas_agg_F1_2,tas_agg_F1_3,tas_agg_F1_4,tas_agg_F1_5,tas_agg_F1_6,tas_agg_F1_7,tas_agg_F1_8,tas_ag
g_F1_9,tas_agg_F1_10)
list_prec85f1<-
list(prec_agg_F1_1,prec_agg_F1_2,prec_agg_F1_3,prec_agg_F1_4,prec_agg_F1_5,prec_agg_F1_6,prec_agg_F1_7,prec_agg_F
1_8,prec_agg_F1_9,prec_agg_F1_10)

F1_85_maxsuit<-matrix(NA,nrow=length(Crops), ncol=length(list_tmin85f1))
rownames(F1_85_maxsuit)<-Crops

for(i in 1:length(Crops)){
  for(j in 1:10){
    Result<-(ecocrop(crop=Crops[i], list_tmin85f1[[j]],list_tas85f1[[j]] ,list_prec85f1[[j]] , rainfed=TRUE))
    maxsuit<-as.vector(Result@maxsuit)
    F1_85_maxsuit[i,j]<-maxsuit
  }
}

F1_85_maxsuit<-as.data.frame(F1_85_maxsuit)
test<-as.matrix(F1_85_maxsuit)
test2<-rowSds(test, cols = 1:10)
mittel<-rowMeans(F1_85_maxsuit)
mittel<-as.vector(mittel)
F1_85_maxsuit$mean<-mittel
F1_85_maxsuit$sd<-test2


################################ FUT2 Period  ###########################

# 2070:2100=FUT2= 32508:43464  -> 43464-32508->  skip= 32507, nrows=10956

F2chain_85_1<-read.csv(";REH;_;CLMCOM-CCLM4_ECEARTH_EUR11_RCP85;.csv", sep=";", skip=32507, nrows = 10956)
colnames(F2chain_85_1) = c("month","year","tmin","tas","precip")
F2chain_85_2<-read.csv(";REH;_;CLMCOM-CCLM4_HADGEM_EUR11_RCP85;.csv", sep=";", skip=32507, nrows = 10956)
colnames(F2chain_85_2) = c("month","year","tmin","tas","precip")
F2chain_85_3<-read.csv(";REH;_;CLMCOM-CCLM4_MPIESM_EUR11_RCP85;.csv", sep=";",  skip=32507, nrows = 10956)
colnames(F2chain_85_3) = c("month","year","tmin","tas","precip")
F2chain_85_4<-read.csv(";REH;_;DMI-HIRHAM_ECEARTH_EUR11_RCP85;.csv", sep = ";", skip=32507, nrows = 10956)
colnames(F2chain_85_4) = c("month","year","tmin","tas","precip")
F2chain_85_5<-read.csv(";REH;_;MPICSC-REMO1_MPIESM_EUR11_RCP85;.csv", sep = ";",skip=32507, nrows = 10956)
colnames(F2chain_85_5) = c("month","year","tmin","tas","precip")
F2chain_85_6<-read.csv(";REH;_;MPICSC-REMO2_MPIESM_EUR11_RCP85;.csv", sep = ";", skip=32507, nrows = 10956)
colnames(F2chain_85_6) = c("month","year","tmin","tas","precip")
F2chain_85_7<-read.csv(";REH;_;SMHI-RCA_ECEARTH_EUR11_RCP85;.csv", sep = ";", skip=32507, nrows = 10956)
colnames(F2chain_85_7) = c("month","year","tmin","tas","precip")
F2chain_85_8<-read.csv(";REH;_;SMHI-RCA_HADGEM_EUR11_RCP85;.csv", sep = ";",skip=32507, nrows = 10956)
colnames(F2chain_85_8) = c("month","year","tmin","tas","precip")
F2chain_85_9<-read.csv(";REH;_;SMHI-RCA_IPSL_EUR11_RCP85;.csv", sep = ";", skip=32507, nrows = 10956)
colnames(F2chain_85_9) = c("month","year","tmin","tas","precip")
F2chain_85_10<-read.csv(";REH;_;SMHI-RCA_MPIESM_EUR11_RCP85;.csv", sep = ";",skip=32507, nrows = 10956)
colnames(F2chain_85_10) = c("month","year","tmin","tas","precip")


chains<-
list(F2chain_85_1,F2chain_85_2,F2chain_85_3,F2chain_85_4,F2chain_85_5,F2chain_85_6,F2chain_85_7,F2chain_85_8,F2chain
_85_9,F2chain_85_10)


tmin_agg_F2<- data.frame(NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col =
rep(NA, 12),NA_col = rep(NA, 12)
                        ,NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12))

tas_agg_F2<- data.frame(NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col =
rep(NA, 12),NA_col = rep(NA, 12)
                       ,NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12))

prec_agg_F2<-data.frame(NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col =
rep(NA, 12),NA_col = rep(NA, 12)
                       ,NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12),NA_col = rep(NA, 12))

for(i in 1:length(chains)){
  tmin_agg<- aggregate(chains[[i]]$tmin ~ chains[[i]]$month, chains[[i]], FUN= mean)
  tmin_agg <- as.vector(tmin_agg[,2])
  tmin_agg_F2[,i]<- tmin_agg
  colnames(tmin_agg_F2)[i]<- paste0("tmin_agg_F2", i)

  tas_agg <- aggregate(chains[[i]]$tas ~ chains[[i]]$month, chains[[i]], FUN= mean)
  tas_agg<- as.vector(tas_agg[,2])
  tas_agg_F2[,i]<-tas_agg
  colnames(tas_agg_F2)[i]<- paste0("tas_agg_F2", i)

  prec_agg<- aggregate(chains[[i]]$precip ~ chains[[i]]$month, chains[[i]], FUN= sum)
  prec_agg<- prec_agg/30
  prec_agg<- as.vector(prec_agg[,2])
  prec_agg_F2[,i]<-prec_agg
  colnames(prec_agg_F2)[i]<- paste0("prec_agg_F2", i)
}

tmin_agg_F2<-as.list(as.data.frame(tmin_agg_F2))
tas_agg_F2<- as.list(as.data.frame(tas_agg_F2))
prec_agg_F2<-as.list(as.data.frame(prec_agg_F2))

for(j in 1:length(tmin_agg_F2)){
  x<-as.vector(tmin_agg_F2[[j]])
  assign(paste0("tmin_agg_F2_",j), x)
}

for(k in 1:length(tas_agg_F2)){
  y<-as.vector(tas_agg_F2[[k]])
  assign(paste0("tas_agg_F2_",k), y)
}

for(l in 1:length(prec_agg_F2)){
  z<-as.vector(prec_agg_F2[[l]])
  assign(paste0("prec_agg_F2_",l), z)
}

##########################################################################

pot_crops<-read.csv("subsetofallcrops_cor.csv", sep=";", na="TRUE")

Crops<-(pot_crops$NAME)
Crops<-as.vector(Crops)

list_tmin85f2<-
list(tmin_agg_F2_1,tmin_agg_F2_2,tmin_agg_F2_3,tmin_agg_F2_4,tmin_agg_F2_5,tmin_agg_F2_6,tmin_agg_F2_7,tmin_agg_F2
_8,tmin_agg_F2_9,tmin_agg_F2_10)
list_tas85f2<-
list(tas_agg_F2_1,tas_agg_F2_2,tas_agg_F2_3,tas_agg_F2_4,tas_agg_F2_5,tas_agg_F2_6,tas_agg_F2_7,tas_agg_F2_8,tas_ag
g_F2_9,tas_agg_F2_10)
```

A.6 Script to map suitability in the reference period

```
#####################################################################################################
#### This script aims to produce raster textfiles that can be read into ArcGIS for all crops on the results table only for the  ####
#### reference period                                                                                ####
#####################################################################################################

setwd("~/projects/Malve_Heinz")

library(ncdf4) # package for netcdf manipulation
library(raster) # package for raster manipulation
library(rgdal) # package for geospatial analysis
library(ggplot2) # package for plotting
library(dismo) # package for ecocrop

####   Remark: when exported, the following needs to be manually pasted in the beginning of the textfiles (without the #)  ####
# NCOLS 241
# NROWS 103
# XLLCORNER 5.750000
# YLLCORNER 45.75000
# CELLSIZE 0.02074689
# NODATA_VALUE -9999

years<-
c("198101010000_198112010000","198101010000_198112010000","198101010000_198112010000","198101010000_198112010
000","198101010000_198112010000",

"198101010000_198112010000","198101010000_198112010000","198101010000_198112010000","198101010000_1981120100
00","198101010000_198112010000",

"198101010000_198112010000","198101010000_198112010000","198101010000_198112010000","198101010000_1981120100
00","198101010000_198112010000",

"198101010000_198112010000","198101010000_198112010000","198101010000_198112010000","198101010000_1981120100
00","198101010000_198112010000",

"198101010000_198112010000","198101010000_198112010000","198101010000_198112010000","198101010000_1981120100
00","198101010000_198112010000",

"198101010000_198112010000","198101010000_198112010000","198101010000_198112010000","198101010000_1981120100
00","198101010000_198112010000")

month1<-matrix(NA,204,103)
month2<-matrix(NA,204,103)
month3<-matrix(NA,204,103)
month4<-matrix(NA,204,103)
month5<-matrix(NA,204,103)
month6<-matrix(NA,204,103)
month7<-matrix(NA,204,103)
month8<-matrix(NA,204,103)
month9<-matrix(NA,204,103)
month10<-matrix(NA,204,103)
month11<-matrix(NA,204,103)
month12<-matrix(NA,204,103)

n<-30
list<-list(month1,month2,month3,month4,month5,month6,month7,month8,month9,month10,month11,month12)
list_tmin<-(lapply(seq_len(n), function(X) list))
list_tas<-(lapply(seq_len(n), function(X) list))
list_prec<-(lapply(seq_len(n), function(X) list))

new_tmin<-list(month1,month2,month3,month4,month5,month6,month7,month8,month9,month10,month11,month12)
new_tas<-list(month1,month2,month3,month4,month5,month6,month7,month8,month9,month10,month11,month12)
new_prec<-list(month1,month2,month3,month4,month5,month6,month7,month8,month9,month10,month11,month12)

for (y in 1:length(years)){
prec<-paste0("~/mnt/Data-Raw-RE/27_Natural_Resources-
RE/99_Meteo_Public/MeteoSwiss_netCDF/historic_71/RhiresM_ch02.lonlat_",years[y],".nc")
tmin<-paste0("~/mnt/Data-Raw-RE/27_Natural_Resources-
RE/99_Meteo_Public/MeteoSwiss_netCDF/historic_71/TminM_ch02.lonlat_",years[y],".nc")
tas<-paste0("~/mnt/Data-Raw-RE/27_Natural_Resources-
RE/99_Meteo_Public/MeteoSwiss_netCDF/historic_71/TabsM_ch02.lonlat_",years[y],".nc")

nc_tmin<-nc_open(tmin)
nc_tas<-nc_open(tas)
nc_prec<- nc_open(prec)

dimlong<-nc_tmin$dim[['lon']]$vals  # 241
dimlat<-nc_tmin$dim[['lat']]$vals   # 103

## third dim: 12 (12 values for each)

reftmin<-ncvar_get(nc_tmin,"TminM")
reftas<-ncvar_get(nc_tas,"TabsM")
refprec<-ncvar_get(nc_prec,"RhiresM")

for (k in 1:12){
  list_tmin[[y]][[k]]<-reftmin[,,k]
 }
for (k in 1:12){
  list_tas[[y]][[k]]<-reftas[,,k]
 }
for (k in 1:12){
  list_prec[[y]][[k]]<-refprec[,,k]
 }
}

# I create lists containing e.g. every month 1 (january) over 30 years

n<-30
matrix_month<-matrix(NA,240,103)
m1<-(lapply(seq_len(n), function(X) matrix_month))
m2<-(lapply(seq_len(n), function(X) matrix_month))
m3<-(lapply(seq_len(n), function(X) matrix_month))
m4<-(lapply(seq_len(n), function(X) matrix_month))
m5<-(lapply(seq_len(n), function(X) matrix_month))
m6<-(lapply(seq_len(n), function(X) matrix_month))
m7<-(lapply(seq_len(n), function(X) matrix_month))
m8<-(lapply(seq_len(n), function(X) matrix_month))
m9<-(lapply(seq_len(n), function(X) matrix_month))
m10<-(lapply(seq_len(n), function(X) matrix_month))
m11<-(lapply(seq_len(n), function(X) matrix_month))
m12<-(lapply(seq_len(n), function(X) matrix_month))

for (y in 1:30){
 m1[[y]]<-list_tmin[[y]][[1]]
 m2[[y]]<-list_tmin[[y]][[2]]
 m3[[y]]<-list_tmin[[y]][[3]]
 m4[[y]]<-list_tmin[[y]][[4]]
 m5[[y]]<-list_tmin[[y]][[5]]
 m6[[y]]<-list_tmin[[y]][[6]]
 m7[[y]]<-list_tmin[[y]][[7]]
 m8[[y]]<-list_tmin[[y]][[8]]
 m9[[y]]<-list_tmin[[y]][[9]]
 m10[[y]]<-list_tmin[[y]][[10]]
 m11[[y]]<-list_tmin[[y]][[11]]
 m12[[y]]<-list_tmin[[y]][[12]]
}

new_tmin[[1]]<-Reduce("+",m1)/length(m1)
new_tmin[[2]]<-Reduce("+",m2)/length(m2)
new_tmin[[3]]<-Reduce("+",m3)/length(m3)
new_tmin[[4]]<-Reduce("+",m4)/length(m4)
new_tmin[[5]]<-Reduce("+",m5)/length(m5)
new_tmin[[6]]<-Reduce("+",m6)/length(m6)
new_tmin[[7]]<-Reduce("+",m7)/length(m7)
new_tmin[[8]]<-Reduce("+",m8)/length(m8)
new_tmin[[9]]<-Reduce("+",m9)/length(m9)
new_tmin[[10]]<-Reduce("+",m10)/length(m10)
new_tmin[[11]]<-Reduce("+",m11)/length(m11)
new_tmin[[12]]<-Reduce("+",m12)/length(m12)

for (y in 1:30){
  m1[[y]]<-list_tas[[y]][[1]]
  m2[[y]]<-list_tas[[y]][[2]]
  m3[[y]]<-list_tas[[y]][[3]]
  m4[[y]]<-list_tas[[y]][[4]]
  m5[[y]]<-list_tas[[y]][[5]]
  m6[[y]]<-list_tas[[y]][[6]]
  m7[[y]]<-list_tas[[y]][[7]]
```

```
colnames(F1chain_85_4) = c("month","year","tmin","tas","precip")
F1chain_85_5<-read.csv("~/mnt/Data-Work-RE/27_Natural_Resources-
RE/271_KLIM_Work/CC_Impacts/Grundlagen/Master_Arbeiten/Msc_Heinz/R_modeling/;REH;_;MPICSC-
REMO1_MPIESM_EUR11_RCP85;.csv", sep = ";",skip= 21549, nrows = 10957)
colnames(F1chain_85_5) = c("month","year","tmin","tas","precip")
F1chain_85_6<-read.csv("~/mnt/Data-Work-RE/27_Natural_Resources-
RE/271_KLIM_Work/CC_Impacts/Grundlagen/Master_Arbeiten/Msc_Heinz/R_modeling/;REH;_;MPICSC-
REMO2_MPIESM_EUR11_RCP85;.csv", sep = ";", skip= 21549, nrows = 10957)
colnames(F1chain_85_6) = c("month","year","tmin","tas","precip")
F1chain_85_7<-read.csv("~/mnt/Data-Work-RE/27_Natural_Resources-
RE/271_KLIM_Work/CC_Impacts/Grundlagen/Master_Arbeiten/Msc_Heinz/R_modeling/;REH;_;SMHI-
RCA_ECEARTH_EUR11_RCP85;.csv", sep = ";", skip= 21549, nrows = 10957)
colnames(F1chain_85_7) = c("month","year","tmin","tas","precip")
F1chain_85_8<-read.csv("~/mnt/Data-Work-RE/27_Natural_Resources-
RE/271_KLIM_Work/CC_Impacts/Grundlagen/Master_Arbeiten/Msc_Heinz/R_modeling/;REH;_;SMHI-
RCA_HADGEM_EUR11_RCP85;.csv", sep = ";", skip= 21549, nrows = 10957)
colnames(F1chain_85_8) = c("month","year","tmin","tas","precip")
F1chain_85_9<-read.csv("~/mnt/Data-Work-RE/27_Natural_Resources-
RE/271_KLIM_Work/CC_Impacts/Grundlagen/Master_Arbeiten/Msc_Heinz/R_modeling/;REH;_;SMHI-
RCA_IPSL_EUR11_RCP85;.csv", sep = ";", skip= 21549, nrows = 10957)
colnames(F1chain_85_9) = c("month","year","tmin","tas","precip")
F1chain_85_10<-read.csv("~/mnt/Data-Work-RE/27_Natural_Resources-
RE/271_KLIM_Work/CC_Impacts/Grundlagen/Master_Arbeiten/Msc_Heinz/R_modeling/;REH;_;SMHI-
RCA_MPIESM_EUR11_RCP85;.csv", sep = ";", skip= 21549, nrows = 10957)
colnames(F1chain_85_10) = c("month","year","tmin","tas","precip")

chains<-
list(F1chain_85_1,F1chain_85_2,F1chain_85_3,F1chain_85_4,F1chain_85_5,F1chain_85_6,F1chain_85_7,F1chain_85_8,F1chain
_85_9,F1chain_85_10)

n <- 10
tmin<-matrix(NA,30, 12)
tmin_agg_FUT1_years <- lapply(seq_len(n), function(X) tmin)
tas<-matrix(NA,30, 12)
tas_agg_FUT1_years <- lapply(seq_len(n), function(X) tas)
prec<-matrix(NA,30, 12)
prec_agg_FUT1_years <- lapply(seq_len(n), function(X) prec)

for(i in 1:length(chains)){
  for (j in 1:12){
    tmin_agg<- aggregate(chains[[i]]$tmin ~ chains[[i]]$month, chains[[i]], c)
    tmin_days<-tmin_agg$`chains[[i]]$tmin`[[j]]
    y<-(length(tmin_days)/30)
    seq <- seq(1, length(tmin_days), y)
    tmin_agg_FUT1_years[[i]][,j] <- sapply(seq, function(x) {mean(tmin_days[x:(x+(y-1))])})
  }
}
for(i in 1:length(chains)){
  for (j in 1:12){
    tas_agg<- aggregate(chains[[i]]$tas ~ chains[[i]]$month, chains[[i]], c)
    tas_days<-tas_agg$`chains[[i]]$tas`[[j]]
    y<-(length(tas_days)/30)
    seq <- seq(1, length(tas_days), y)
    tas_agg_FUT1_years[[i]][,j] <- sapply(seq, function(x) {mean(tas_days[x:(x+(y-1))])})
  }
}
for(i in 1:length(chains)){
  for (j in 1:12){
    prec_agg<- aggregate(chains[[i]]$prec ~ chains[[i]]$month, chains[[i]], c)
    prec_days<-prec_agg$`chains[[i]]$prec`[[j]]
    y<-(length(prec_days)/30)
    seq <- seq(1, length(prec_days), y)
    prec_agg_FUT1_years[[i]][,j] <- sapply(seq, function(x) {sum(prec_days[x:(x+(y-1))])})
  }
}
n <- 22
suit_years<-matrix(NA,30,10)
crops_var_FUT1 <- lapply(seq_len(n), function(X) suit_years)

for (i in 1:length(crops_85)){
  for(j in 1:10){
    for (k in 1:30){
      Result<-(ecocrop(crop=crops_85[i], tmin_agg_FUT1_years[[j]][k,],tas_agg_FUT1_years[[j]][k,],prec_agg_FUT1_years[[j]][k,],
rainfed=TRUE))
      maxsuit<-as.vector(Result@maxsuit)
      crops_var_FUT1[[i]][k,j]<-maxsuit
    }
  }
}
for (i in 1:length(crops_85)){
  for(j in 1:10){
    var[[i]][j,3]<-mean(crops_var_FUT1[[i]][,j])
    var[[i]][j,4]<-sd(crops_var_FUT1[[i]][,j])
  }
}

################################################## FUT2 period ##################################################

F2chain_85_1<-read.csv("~/mnt/Data-Work-RE/27_Natural_Resources-
RE/271_KLIM_Work/CC_Impacts/Grundlagen/Master_Arbeiten/Msc_Heinz/R_modeling/;REH;_;CLMCOM-
CCLM4_ECEARTH_EUR11_RCP85;.csv", sep=";", skip=32507, nrows = 10956)
colnames(F2chain_85_1) = c("month","year","tmin","tas","precip")
F2chain_85_2<-read.csv("~/mnt/Data-Work-RE/27_Natural_Resources-
RE/271_KLIM_Work/CC_Impacts/Grundlagen/Master_Arbeiten/Msc_Heinz/R_modeling/;REH;_;CLMCOM-
CCLM4_HADGEM_EUR11_RCP85;.csv", sep=";", skip=32507, nrows = 10956)
colnames(F2chain_85_2) = c("month","year","tmin","tas","precip")
F2chain_85_3<-read.csv("~/mnt/Data-Work-RE/27_Natural_Resources-
RE/271_KLIM_Work/CC_Impacts/Grundlagen/Master_Arbeiten/Msc_Heinz/R_modeling/;REH;_;CLMCOM-
CCLM4_MPIESM_EUR11_RCP85;.csv", sep=";",  skip=32507, nrows = 10956)
colnames(F2chain_85_3) = c("month","year","tmin","tas","precip")
F2chain_85_4<-read.csv("~/mnt/Data-Work-RE/27_Natural_Resources-
RE/271_KLIM_Work/CC_Impacts/Grundlagen/Master_Arbeiten/Msc_Heinz/R_modeling/;REH;_;DMI-
HIRHAM_ECEARTH_EUR11_RCP85;.csv", sep = ";", skip=32507, nrows = 10956)
colnames(F2chain_85_4) = c("month","year","tmin","tas","precip")
F2chain_85_5<-read.csv("~/mnt/Data-Work-RE/27_Natural_Resources-
RE/271_KLIM_Work/CC_Impacts/Grundlagen/Master_Arbeiten/Msc_Heinz/R_modeling/;REH;_;MPICSC-
REMO1_MPIESM_EUR11_RCP85;.csv", sep = ";",skip=32507, nrows = 10956)
colnames(F2chain_85_5) = c("month","year","tmin","tas","precip")
F2chain_85_6<-read.csv("~/mnt/Data-Work-RE/27_Natural_Resources-
RE/271_KLIM_Work/CC_Impacts/Grundlagen/Master_Arbeiten/Msc_Heinz/R_modeling/;REH;_;MPICSC-
REMO2_MPIESM_EUR11_RCP85;.csv", sep = ";", skip=32507, nrows = 10956)
colnames(F2chain_85_6) = c("month","year","tmin","tas","precip")
F2chain_85_7<-read.csv("~/mnt/Data-Work-RE/27_Natural_Resources-
RE/271_KLIM_Work/CC_Impacts/Grundlagen/Master_Arbeiten/Msc_Heinz/R_modeling/;REH;_;SMHI-
RCA_ECEARTH_EUR11_RCP85;.csv", sep = ";", skip=32507, nrows = 10956)
colnames(F2chain_85_7) = c("month","year","tmin","tas","precip")
F2chain_85_8<-read.csv("~/mnt/Data-Work-RE/27_Natural_Resources-
RE/271_KLIM_Work/CC_Impacts/Grundlagen/Master_Arbeiten/Msc_Heinz/R_modeling/;REH;_;SMHI-
RCA_HADGEM_EUR11_RCP85;.csv", sep = ";",skip=32507, nrows = 10956)
colnames(F2chain_85_8) = c("month","year","tmin","tas","precip")
F2chain_85_9<-read.csv("~/mnt/Data-Work-RE/27_Natural_Resources-
RE/271_KLIM_Work/CC_Impacts/Grundlagen/Master_Arbeiten/Msc_Heinz/R_modeling/;REH;_;SMHI-
RCA_IPSL_EUR11_RCP85;.csv", sep = ";", skip=32507, nrows = 10956)
colnames(F2chain_85_9) = c("month","year","tmin","tas","precip")
F2chain_85_10<-read.csv("~/mnt/Data-Work-RE/27_Natural_Resources-
RE/271_KLIM_Work/CC_Impacts/Grundlagen/Master_Arbeiten/Msc_Heinz/R_modeling/;REH;_;SMHI-
RCA_MPIESM_EUR11_RCP85;.csv", sep = ";",skip=32507, nrows = 10956)
colnames(F2chain_85_10) = c("month","year","tmin","tas","precip")

chains<-
list(F2chain_85_1,F2chain_85_2,F2chain_85_3,F2chain_85_4,F2chain_85_5,F2chain_85_6,F2chain_85_7,F2chain_85_8,F2chain
_85_9,F2chain_85_10)

n <- 10
tmin<-matrix(NA,30, 12)
tmin_agg_FUT2_years <- lapply(seq_len(n), function(X) tmin)
tas<-matrix(NA,30, 12)
tas_agg_FUT2_years <- lapply(seq_len(n), function(X) tas)
prec<-matrix(NA,30, 12)
prec_agg_FUT2_years <- lapply(seq_len(n), function(X) prec)

for(i in 1:length(chains)){
  for (j in 1:12){
    tmin_agg<- aggregate(chains[[i]]$tmin ~ chains[[i]]$month, chains[[i]], c)
    tmin_days<-tmin_agg$`chains[[i]]$tmin`[[j]]
    y<-(length(tmin_days)/30)
    seq <- seq(1, length(tmin_days), y)
    tmin_agg_FUT2_years[[i]][,j] <- sapply(seq, function(x) {mean(tmin_days[x:(x+(y-1))])})
```

Declaration of consent

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

Name/First Name: Heinz, Malve Maria

Registration Number: 19-119-494

Study program: Climate Sciences

Bachelor ☐ Master ☑ Dissertation ☐

Title of the thesis: Prospects of cultivating alternative crops in a changing climate in Switzerland

Supervisor: PD Dr. Annelie Holzkämper
Prof. Dr. Olivia Romppainen-Martius

I declare herewith that this thesis is my own work and that I have not used any sources other than those stated. I have indicated the adoption of quotations as well as thoughts taken from other authors as such in the thesis. I am aware that the Senate pursuant to Article 36 paragraph 1 litera r of the University Act of 5 September, 1996 is authorized to revoke the title awarded on the basis of this thesis.
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