LIFE-ADVICLIM PROJECT: RÜDESHEIM (RHEINGAU) PILOT SITE

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LIFE-ADVICLIM PROJECT: RÜDESHEIM (RHEINGAU) PILOT SITE

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DRAFT

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Table of contents

DRAFT

FOREWORD

There is growing evidence that climate change is taking place throughout the world. Observed regional changes include rising temperatures, shifts in rainfall patterns and extreme weather events. Climate change is expected to continue in the near future, and have important consequences on viticulture. These vary from short-term impacts on wine quality and style, to long-term issues, such as varietal suitability and the economic sustainability of traditional wine producing areas. As a result, the wine industry is facing many challenges, which include adapting to these potential impacts, as well as reducing greenhouse gas emissions related to their activities.

In response to these challenges, the LIFE-ADVICLIM project aims to evaluate and develop local climate change adaptation and mitigation strategies. This project's measurement network and web platform will inform vinegrowers on climate change impacts, rational adaptation scenarios and greenhouse gas emissions related to their practices at the vineyard scale. These technologies are evaluated in several European wine growing regions (Figure 1), namely Bordeaux and Loire Valley (France), Sussex (England), Rheingau (Germany) and Cotnari (Romania). The region of Navarra (Ausejo and Carbonera vineyards) in Spain is an associate study area. These six regions represent the climatic diversity of European wine producing areas, ranging from the Mediterranean to oceanic and continental climates.

For more information on this project, visit www.adviclim.eu

Figure 1: Position of the six European wine growing regions studied in the LIFE-ADVICLIM project.

INTRODUCTION

Climate is changing across the word, especially through an increase in temperatures and the modification of rainfall, which can increase the risk for water deficit and fungal diseases. Vine development and grape composition are strongly related to climate, hence climate modification is a major challenge for wine production.

In this context, the aim of the Life-ADVICLIM project is to evaluate and develop local climate change adaptation and mitigation strategies.

This report presents the main results obtained in the Rüdesheim pilot site (Rheingau, Germany) for the B3 action, which aims to synthesize all the Life-ADVICLIM results.

General presentation of Rheingau pilot site

The Rheingau is one of the thirteen German winegrowing regions. In the Rheingau, grapevines are cultivated on an area of 3191 ha (Destatis, 2018). The Rheingau is physiographically divided into the regions upper and lower Rheingau. The upper Rheingau includes the main part of the cultivation along approx. 25 km and 3-6 km width between Wiesbaden and Rüdesheim, bounded by Rhine River to the south and the ridge of the Taunus mountain range in the north, and the vineyards near Hochheim on the Main River. Grapevines are cultivated between approx. 80-280 m altitude, forming a gently rolling hillscape. For most of the region the soils developed from loess or sandy loess as parent material. They are fertile and have a balanced water budget. Soil erosion, intensified by agriculture over thousands of years, filled dells and in conjunction with soil formation by a variety of basement rocks (sand, clay, marl, limestone), led to the further differentiation of soils, where the loess layers were thin. The soils of the lower Rheingau in the west of Rüdesheim are very different. The Rhine flows here to the north into the Middle Rhine valley with its steep slopes. The parent material of the soil formation consists mainly of shallow glacial solifluction layers containing a lot of basement rock (sandstone, quartzite, slate). These soils are nutrient-poor, stony and shallow and have generally low available water capacity (Löhnertz et al. 2004, Böhm et al., 2007). The Riesling is with 78 % of the growing area the most important grapevine variety, followed by Pinot Noir (12 %), Pinot Blanc (1.6 %) and Müller-Thurgau (1 %) (Destatis 2018).

The climate is oceanic and temperate, with a total mean annual rainfall of 544 mm, and a mean annual temperature of 10.5 °C (Data: *Deutsche Wetterdienst, station Geisenheim*, average 1981-2010). Rainfall is well distributed throughout the year. The months with the lowest rainfall are with 35 mm February and April and the highest rainfall occurs in July with 60 mm.

Objective of the LIFE-ADVICLIM Action B3 (Figure 2) for the Rheingau region

In order to characterize temperature variability over this pilot site a small scale network of 30 temperature sensors was used to link the temperature with grapevine development and berry composition. Phenology, grape quality and yield was monitored around every temperature sensor.

Using this measurement and observation network, the study of the variability between temperature and grapevine development at a local scale becomes possible. The spatial distribution of temperature was analysed, and temperature maps were produced. The

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grapevine response to temperature variability was studied, as well as the relationship between temperature, grape composition and yield.

The climate and phenological models developed in this first step permitted the downscaling of regional climate models to a local scale. This was then coupled with regional climate change models based on the greenhouse gas (GHG) concentration scenarios RCP (Representative Concentration Pathway) 4.5 and 8.5, and the effect on vine development assessed.

Five plots, representing the diversity of this pilot site in terms of environmental and cultivation characteristics, were selected. These plots enabled the characterisation of current cultural practices, and the modelling of their evolution according to different climate change scenarios. These results informed the development of adaptation scenarios at the vineyard scale, in order to support vinegrowers in their efforts to cope with climate change.

The sustainability of viticultural practices at the present time and in the future was evaluated in terms of the production of GHG emissions, environmental impacts and socio-economic impact.

All these results provide key climate change adaptation and mitigation information for local vinegrowers.

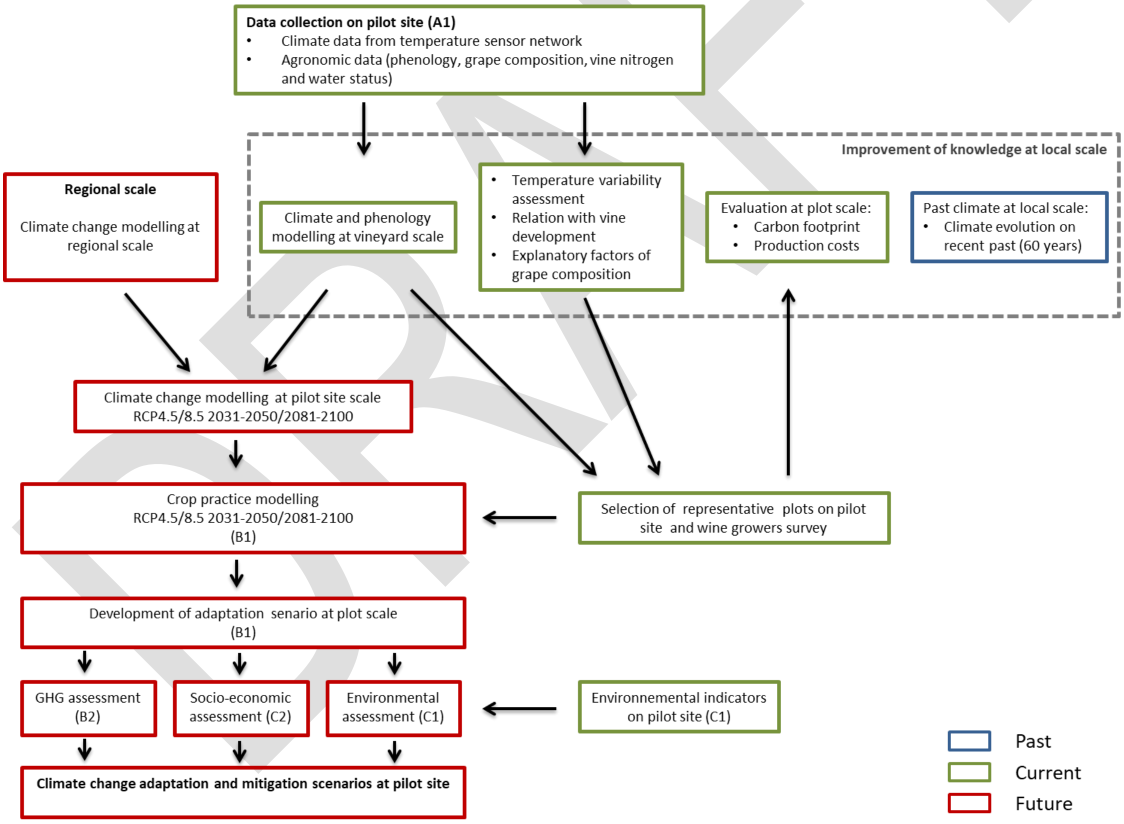

Figure 2: Synthesis of the B3 action

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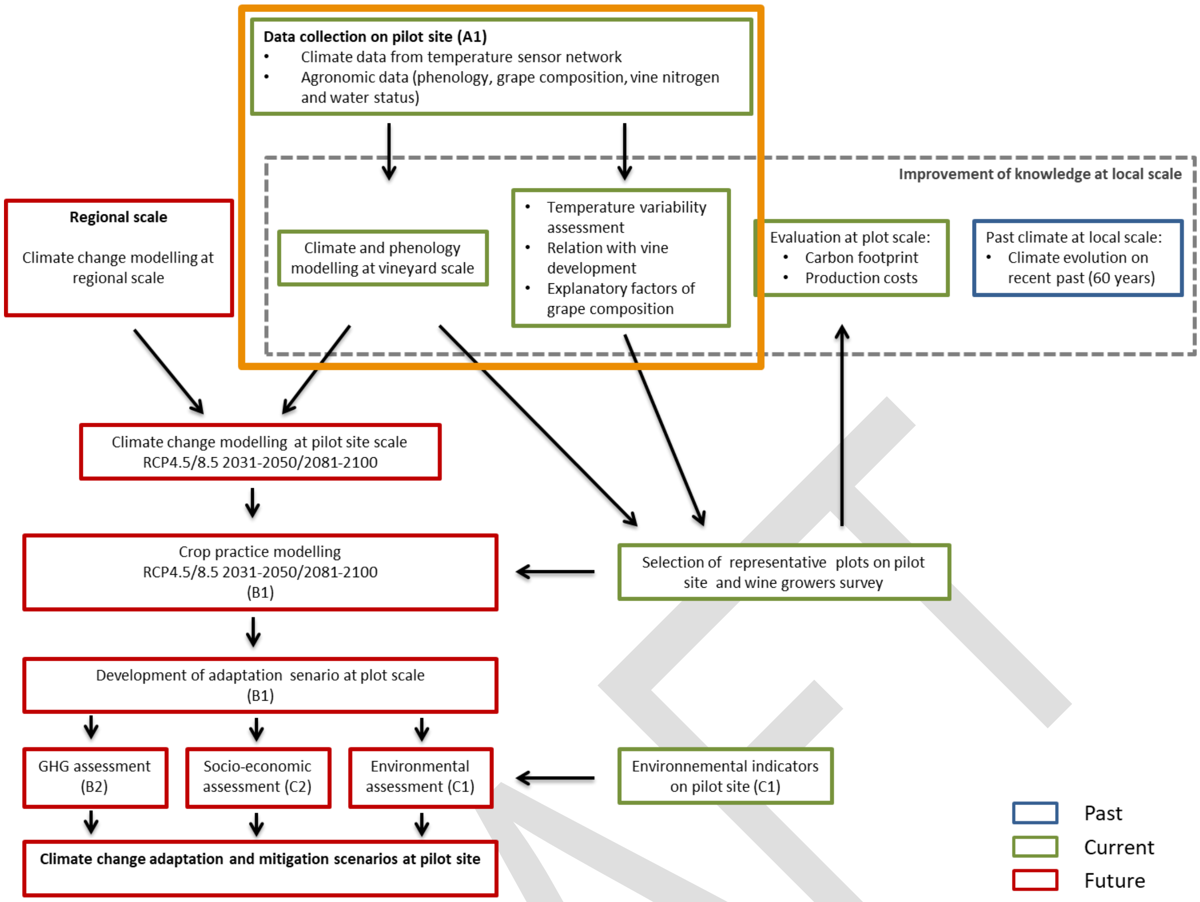
PART 1: FROM OBSERVATION TO MODELISATION AT THE VINEYARD SCALE: AN IMPROVEMENT ON TERROIR ANALYSIS



In this ADVICLIM project action, an experimental protocol was implemented, designed to provide key inputs on temporal and spatial variability in viticulture. The Rüdesheim (Rheingau) pilot site was equipped with a network of temperature data loggers, where climatic and agronomic observations were carried out at the vineyard plot level. These field observations were integrated into a spatial analysis model, combined with orographic features represented by a digital elevation model. The results generated could be linked to regional climate change projections, due to a better understanding of the local climate and of grapevine performance. Coupling bottom-up with top-down models allowed the construction of high-resolution outputs of current and future agro-climatic potentials.

1.1 Agro-climatic measurements implemented at the vineyard scale

1.1.1 Temperature network

In order to characterise the temperature variability of the Rheingau, a subarea of 180 ha in the west of Rüdesheim was chosen and equipped with 30 temperature sensors (the number changed slightly from 29 to 31 during the project time, because of vandalism, technical problems or grubbing up of single plots). Two weather stations (maintained by the Hochschule

Geisenheim and the Rheingauer Weinbauverband) with a wireless data transmission system were already in place and could also be used by the ADVICLIM project. The terrain of this subarea is very variable and characterized by steep slopes (up to 70 %), dry walls, deep side valleys, terraces and hills. Therefore, the area is well-suited to study local temperature variability within those landscapes. The sensors were installed on plots planted with the variety Riesling on many different combinations of altitude, slope and aspect in order to take into account the impact of the terrain (Figure 3) on temperature.

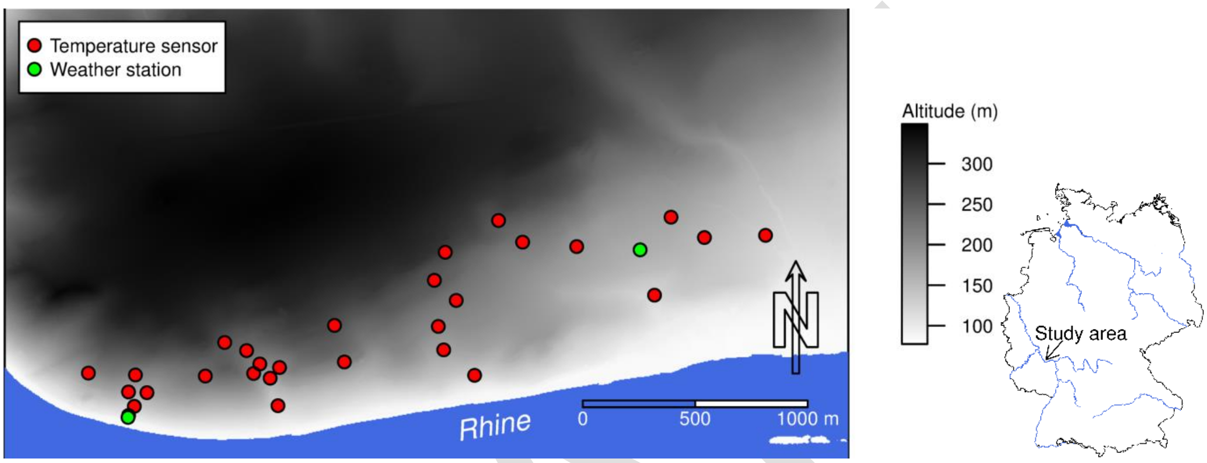


Figure 3: Localisation of temperature sensors near Rüdesheim on the Rhine river projected on a Digital Elevation Model.

The temperature sensor/logger system used in Rüdesheim was the HOBO U23 Pro v2 external Temperature/Relative Humidity Data Logger (Onset, Bourne, Us). These sensors were installed on vine posts at begin or end of vineyard plot rows in order to avoid overgrowing of the sensors by the grapevines. The sensors recorded temperature every 10 minutes. In 2015, extensive tests with a wireless system (WiSenSys, Scatter100) from a German distributor (UPGmbH, Ibbenbüren) were made but this system failed to work properly because of the features of the terrain. Because of the existence of already two wireless weather stations, the size of the area, the accuracy of the HOBO sensors (±0.21 °C) and to avoid loss of data, it was decided to install the HOBO sensors. The data were manually collected every three months and sent to the VIDAC platform. The temperature data of the weather stations were sent automatically daily to the VIDAC platform.

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1.1.2 Ecophysiological measurements

Ecophysiological measurements were carried out in order to monitor grapevine development (phenology) and berry composition.

In the Rüdesheim pilot site grapevine phenology was monitored at the 30 positions where the temperature sensors were installed. The modified E-L system (Coombe, 1995) was used to identify the stages budburst (E-L number 4), full bloom (E-L Number 23) and veraison (begin of ripening, E-L number 35). For budburst and full bloom 12 vines around the sensors were examined. Veraison was identified by the date when the sugar accumulation starts. This is typical the case when the must density of grapes reaches 25 °Oechsle (≙ 6.9 °Brix, E-L number 35). Therefore, samples of six bunches taken from different grapevines around the sensors were collected and analysed in close intervals until 25 °Oechsle or more were measured. To control differences of maturity, six bunches per sensor were collected for all sensors on the same day close to begin of harvest in the region and the must density, total acidity and pH was analysed. Yield was calculated in the years 2017 and 2018 on the basis of the mean bunch weight of the six bunches, mean bunch number per vine (mean of six vines) and the planting density.

1.2 Temperature analysis at the local scale

1.2.1 Climate evolution in the recent past

According to IPCC (2013), the global mean surface temperature increased during the 20th century by 0.85 °C, which has also altered the climate of all studied global wine regions (Jones et al., 2005). Starting from this general finding, the changes of the viticultural climate suitability that occurred during the period 1951-2010 of the ADVILCIM pilot sites were examined.

Based on the data of the weather station Geisenheim (Station-ID 1580, Deutscher Wetterdienst), which is located within the Rheingau winegrowing region, the changes of viticultural suitability were analysed by comparing long-term climate parameters and bioclimatic indices for the periods 1951-1980 and 1981-2010 (Table 1). The warming in the region is reflected by an increase of the annual mean temperature (+0.7 °C), the absolute minimum temperature (+4.6 °C) and the absolute maximum temperature (+0.4 °C). Ice days (Tmax < 0 °C) decreased slightly by 2 days and hot days (Tmax > 30 °C) increased by 5 days. Also sunshine hours increased, likely because of a strong reduction of the aerosol concentration in the atmosphere in the 1990ties (Wild et al., 2005). No change was observed for precipitation. The warming is also reflected by an increase of bioclimatic indices. The average growing season temperature (Apr-Oct; AvGST; Jones, 2005) increased by 0.7 °C. Concerning the classification of Jones et al. (2005) based on data from 1950 to 1999 of 27 wine producing regions, this corresponds to a cool but an intermediate growing region. The AvGST of 15.2 °C for the Rheingau (1981-2010) corresponds to the value of 15.3 °C reported by Jones et al. (2005) for the Loire Valley or Burgundy for the period 1950-1999. Concerning the Winkler-Index, the Rheingau changed from region Ia to region Ib. The Huglin-Index increased by 157 degree-days and but is classified for both periods in the cool climate class (HI-2, 1500 < HI ≤ 1800) but with respect to the interannual variability of the temperature, 14 years were „very cool" (HI-3, HI < 1500) during 1951-1980 and only 4 during 1981-2010.

Table 1. Evolution of several climate parameters and bioclimatic indices for the station Geisenheim (Rheingau) for the time periods 1951-1980 and 1981-2010.

Climate parameter / Bioclimatic indice	**From 1951 to 1980**	**From 1981-2010**	**1981-2010 minus 1980-1951**
Absolute Tmin (°C)	-21.5	-16.9	+4.6
Absolute Tmax (°C)	37.4	37.8	+0.4
Annual mean temperature (°C)	9.8	10.5	+0.7

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Annual precipitation (mm)	534	543	+9
Annual sunshine hours (h)	1597	1648	+51
Ice days (Tmax < 0 °C)	14	12	-2
Hot days (Tmax > 30 °C)	6	11	+5
AvGST (°C)	14.5	15.2	+0.7
Winkler-Index (degree-days)	1081	1244	+163
Huglin-Index (degree-days)	1530	1687	+157

1.2.2 Temperature variability of the vegetative season

The daily mean (Tmean), minimum (Tmin) and maximum temperatures (Tmax) were analysed during the growing season (from April 1st to October 31th) during three consecutive years (2016-2018) (Figure 4) based on the temperature sensors installed in the Rüdesheim pilot site. The mean temperature in Figure 4 is equivalent to the AvGST (Jones, 2005) analysed for the recent past in paragraph 1.2.1 for the weather station in Geisenheim, which is approx. 3 km away from the Rüdesheim area. Concerning the temperature, the years 2016 and 2017 were quite similar. But the AvGST of both years is with 16.0 °C (2016) and 16.1 °C (2017) distinctly (+0.8 °C, resp. +0.9 °C) warmer than the long-term mean from 1981-2010 of Geisenheim, showing ongoing warming due to climate change. The year 2018 was with an AvGST of 18.2 °C in the mean for the Rüdesheim area extremely warm. In Geisenheim, 2018 was with an AvGST of 17.8 °C the warmest year on record since data recording started in 1884 and was in comparison with the station Bordeaux-Merignac warmer than nearly all years from 1946-1988 (beside of 1947 and 1949) recorded at this station. The spatial variability of the AvGST is in the range of 1.2 °C for all three years and is comparable with the interannual variability of this parameter of the weather station Geisenheim. This is reasonable because a larger spatial variability would mean that it would be maybe too cold for parts of the growing region to achieve sufficient qualities in unfavourable years. The spatial variability of Tmax is with 2.5 °C more than the double compared to Tmean. As Tmax is mainly determined by the weather condition during daytime, especially sunshine, this shows the impact of landscape features on microclimate. The forest in the north of the Taunus mountain range has probably a cooling effect but steep slopes, dry walls and the terrain in general seemed to create hotspots within the region leading to a large spatial variability of the daily maximum temperature. The minimum temperature during night is not affected by sunshine but more by the general weather conditions and long wave radiative exchange with the atmosphere. Tmin is therefore less influenced by terrain features and shows therefore less spatial variability.

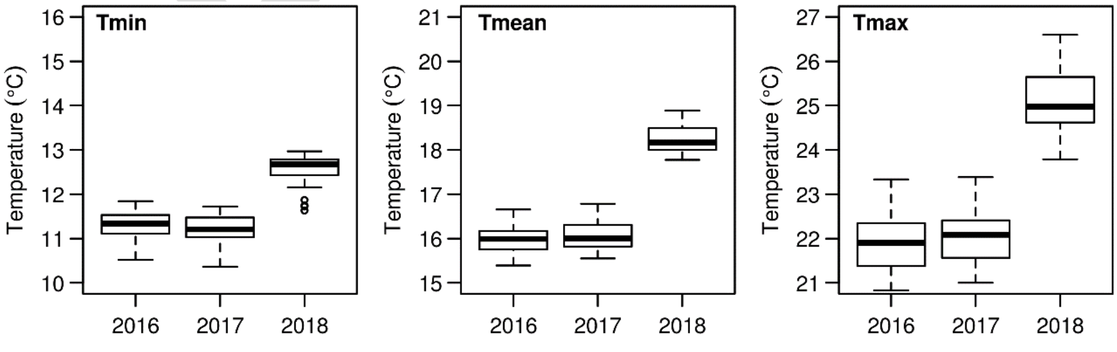

Figure 4: Boxplots of minimum, mean and maximum daily temperatures (average over the growing season from April to October) for thirty temperature loggers installed in the west of Rüdesheim (Rheingau) from 2016 to 2018.

1.2.3 Bioclimatic Indices: Huglin-Index

The Heliothermal Index of Huglin (Huglin, 1978) is used to classify winegrowing regions concerning their climatic conditions as well as to classify grapevine varieties concerning their (minimum) heat requirements. Like the Winkler-Index, the Huglin-Index is based on a temperature summation (from April 1st to September 30th) but depends also on a day-length factor and a stronger weight of the maximum temperature, both factors are correlated with sunshine duration.

The mean Huglin-Index of the years 2016 (HI = 1960) and 2017 (HI = 1901) exceeded the long-term mean (1981-2010) of Geisenheim of 1687 (Figure 5). Both years can be classified to the temperate class HI-1 (1800 < HI ≤ 2100) and the associated grapevine varieties for this class are Cabernet Sauvignon, Ugni Blanc and Syrah (Tonietto and Carbonneau, 2004). The Huglin-Index of the extreme warm year 2018 was 2458, which corresponds to the "warm" class HI+2 (2400 < HI ≤ 3000). Following Tonietto and Carbonneau (2004) this class „exceeds the heliothermal needs to ripen the varieties, even the late ones". The spatial variability of the Huglin-Index is around 370 and stable for all three years and spans a little bit more than one climate class. The spatial variability is comparable to the variability from year to year recorded at the weather station of Geisenheim. Beside of the extreme warm years 2003 and 2018, the Huglin-Index varies since 1997 from minimum of 1630 (year 1998) to maximum 1943 (year 2009).

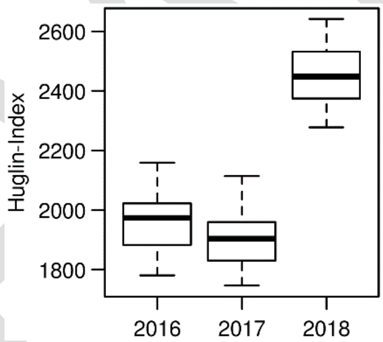

Figure 5: Boxplots of Huglin-Index for the years 2016-2018, based on data of 30 temperature loggers in the West of Rüdesheim (Rheingau).

1.2.4 Climate modelling adapted to the vineyard scale

1.2.4.1 Fine scale modelling

The non-linear regression model (SVR) presented in action A1 (Le Roux et al., 2017) was used to map temperatures at the Rüdesheim pilot site.

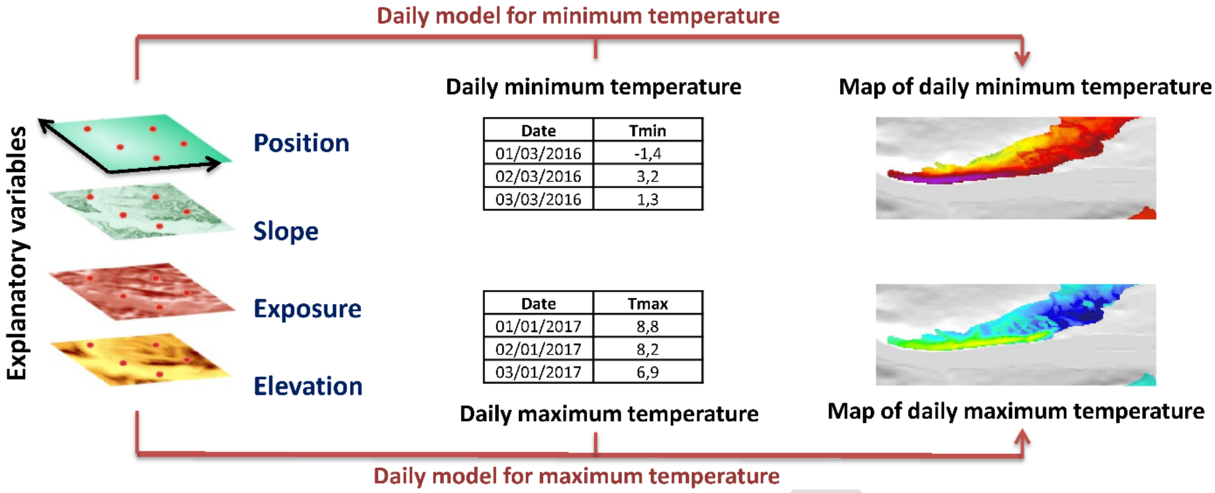

Figure 6: Schematic synthesis of the production of daily temperature maps

Using the data extracted from the data loggers, the model allows the mapping of the daily maximum and minimum temperatures over the studied years (2016-2017; Figure 6) and the spatial analysis of the relationships between the temperature distribution and the local environment. Based on these daily maps, the average minimum and maximum temperatures and the bioclimatic indices mentioned above were mapped in order to visualise their spatial variability.

1.2.4.2 Climate modelling results

The models (Tmin, Tmax, HI) show a recurring spatial structure as well as a vintage effect. It was therefore decided to average all the temperature maps in order to be able to quantify the temperature distribution and produce a temperature zoning.

1.2.4.2.1 Spatial distribution of minimum and maximum temperatures during the vegetative season

The analysis of the average minimum (Tmin) and maximum (Tmax) temperature maps over the studied years revealed a high spatial variability, but also with different spatial patterns (Figure 7). The lowest area of the region in the near of the Rhine river correspond to the areas with the highest temperature for Tmin as well as Tmax. Comparably high (Tmin) appear also in two small gorges in the western part of the pilot site. But in the eastern part, adjacent to the town Rüdesheim, where the slope is less compared to the eastern part, the Tmax is quite high and Tmin quite low. The northern part with higher altitude, adjacent to the forest of the Taunus Mountain range, correspond with the lowest Tmax temperatures but medium Tmin temperatures and show the lowest amplitude between nighttime (Tmin) and daytime (Tmax) temperatures.

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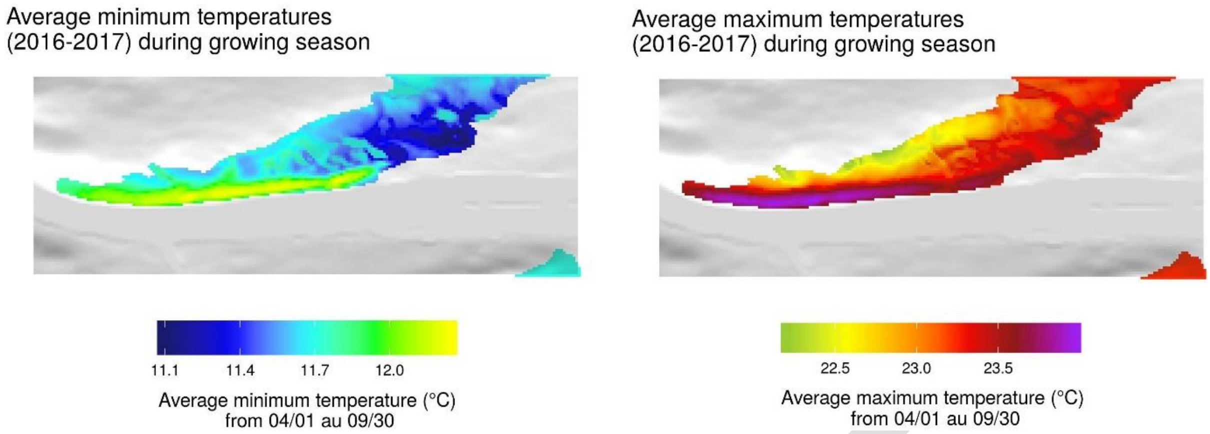

Figure 7: Spatial distribution of average minimum and maximum temperatures during the growing season (2016-2017)

1.2.4.2.2 Spatial distribution of the Huglin-Index

The spatial distribution of the Huglin-Index (Figure 8) is quite comparable with the distribution of the Tmax temperature. The regions with high values for the Huglin-Index are strongly associated with the lowest part adjacent to the Rhine River, medium values appear in the more flat eastern part and the lowest values appear in the higher regions, adjacent the forest.

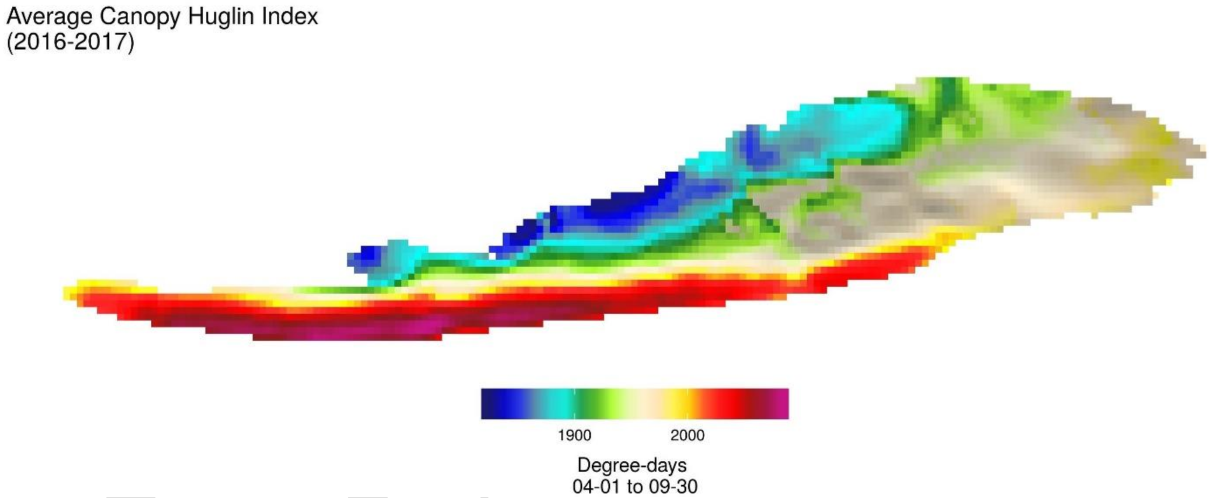

Figure 8: Spatial distribution of the Huglin-Index (2016-2017)

1.3 Vine response to spatial temperature variability

1.3.1 Phenological observations

The dates of phenological events were monitored on 30 plots of Riesling from 2016 to 2019 (Figure 9; 2019 not shown in the diagram). Differences in the phenological development between the years can be explained by different temperature patterns. Cold temperatures in March and warm temperatures in April (compared to long term means from 1981-2010) caused a normal budburst around the 20th of April for the years 2016 and 2018. Budburst in 2017 was very early because of a warm March (warmest March since 1884, were data recording started, referring to the weather station of Geisenheim). The warm April 2018 (third warmest on record) followed by the warm May 2018 (second warmest on record) caused that the stage full bloom appeared very early in 2018 (around end of May). The lead in phenological development of the year 2018 compared to the years 2017 and 2016 preserved until the stage of veraison, as well as the lead of 2017 to 2016. The difference from year to year is stronger (about three weeks between 2018 and 2016) as the spatial difference within the region, which is about 14 days. Interestingly, an earlier and warmer ripening period, does not lead in general to an increase of the sugar content of the must at harvest. This was probably an effect of a dry spell since July in the year 2018, whereas the water supply was quite good during ripening in 2017. In 2017, the warmer plots had also higher sugar content. But in 2018, some of the warmest plots at steep slopes with low available water capacity showed a strong reduction of sugar accumulation because of the high level of drought stress and the plots with higher must weights were found at higher altitudes near the forest with better water supply.

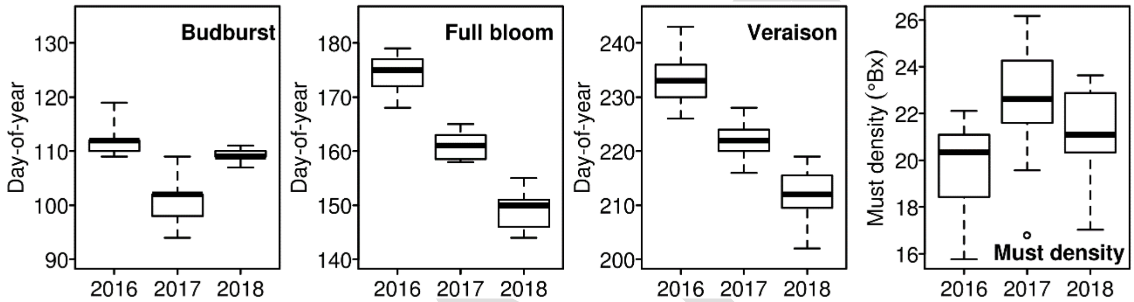

Figure 9: Boxplots of phenological observations (first three plots) and the must density (last plot) from 2016 to 2018. Samples for must density were taken on 22 Sep 2016, 19 Sep 2017, 13 Sep 2018 showing differences of grape ripening in the region.

1.3.2 Phenological model for the Rheingau

The Grapevine Floraison – Veraison (GFV) model is a simple linear temperature summation model (Parker et al., 2011; Parker et al., 2013) which sums the temperature degrees exceeding 0 °C (growing degree days, GDD) starting from the 60th day of the year up to the flowering (stage full bloom) (F) and to the veraison (V). The original parameterization of this model offers robustness, especially when testing its response to temperature variations (Parker et al., 2011). For this reason, the GFV-model is used in the ADVICLIM project to elaborate the forecasts for grapevine flowering and veraison in the perspective of the climatic change.

In order to test the suitability of the GFV-model, we calculated threshold values of the temperature summation for full bloom and veraison of the three warmest and coldest plots of the pilot site for the years 2016-2018. Parker et al. (2011) reported threshold values for Riesling and stage full bloom of 1249 and 2590 for veraison, which fit very well to the values of 1261 and 2605 we found for the average of three years and the six plots of the pilot site. The mean increase from day to day of the GFV-sum is 18.2 GDD in June (flowering) and 19.5 GDD in August (veraison; based on data from Geisenheim from 1990-2019), so the difference between the results of Parker et al. (2011) and the results from the Rheingau pilot site are within a step of one day. Interestingly, the threshold values for the stage full bloom of the warm plots are in all years slightly lower than the values for the cold plots. This additional earlier development of the warm plots compared to the cold plots, which cannot be reproduced by the GFV-model, is in the range of 2-5 days. The variability from year to year of the GFV-model is with 256 GDD (2018 minus 2016, corresponding to 14 days) much stronger. Again, under the warm conditions in spring of the year 2018 the threshold value is lower than the long term mean. Parker et al. (2011) reported a mean error of ± 6 days for the accuracy of the GFV-model to predict full bloom (flowering). For the onset of veraison the observed variability between cold and warm plots and also the variability from year to year is lower and is in the range of 5 days. Therefore, we can overall conclude, that our observations are in line with the results of Parker et al. (2011) and that the GFV-model is appropriate to predict spatial and temporal variations of both phenological stages. On the other side, our observations show also the limits of the GFV-model, which are related to natural variability, the general precision of phenological observations and other factors, which are not captured by the simple (but robust) approach of the GFV-model. We therefore conclude, that the spatial and temporal variability of phenology predicted with the GFV-model is slightly underestimated compared to observations.

Table 2. Threshold values for the phenological stages full bloom and veraison for the variety Riesling based on the GFV temperature summation model (Parker et al., 2011).

Years	Cold plots			Warm plots			Average
	#15	#12	#14	#30	#27	#9	
	Sum of temperatures for stage full-bloom						
2016	1387	1388	1404	1348	1319	1339	1364
2017	1320	1322	1340	1315	1306	1277	1313
2018	1188	1127	1163	1058	1047	1071	1108
Average	1298	1279	1302	1240	1244	1229	1261
	Sum of temperatures for stage veraison						
2016	2671	2542	2589	2676	2584	2619	2614
2017	2626	2550	2627	2640	2615	2650	2618
2018	2603	2589	2661	2568	2527	2553	2584
Average	2633	2560	2626	2628	2575	2607	2605

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Conclusion part 1

Figure 10 is a schematic synthesis of the first part of this report, which investigates the terroir of the Rheingau (Rüdesheim) region.

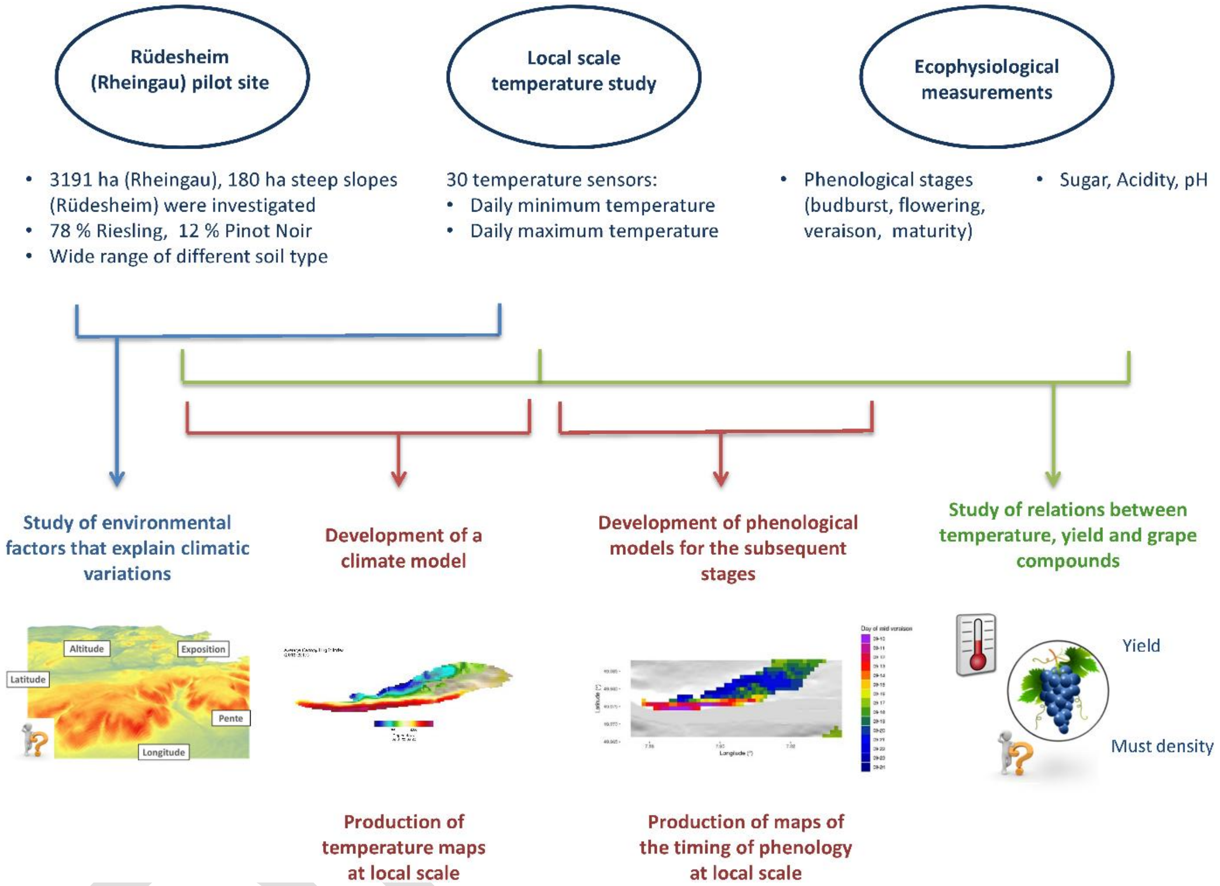
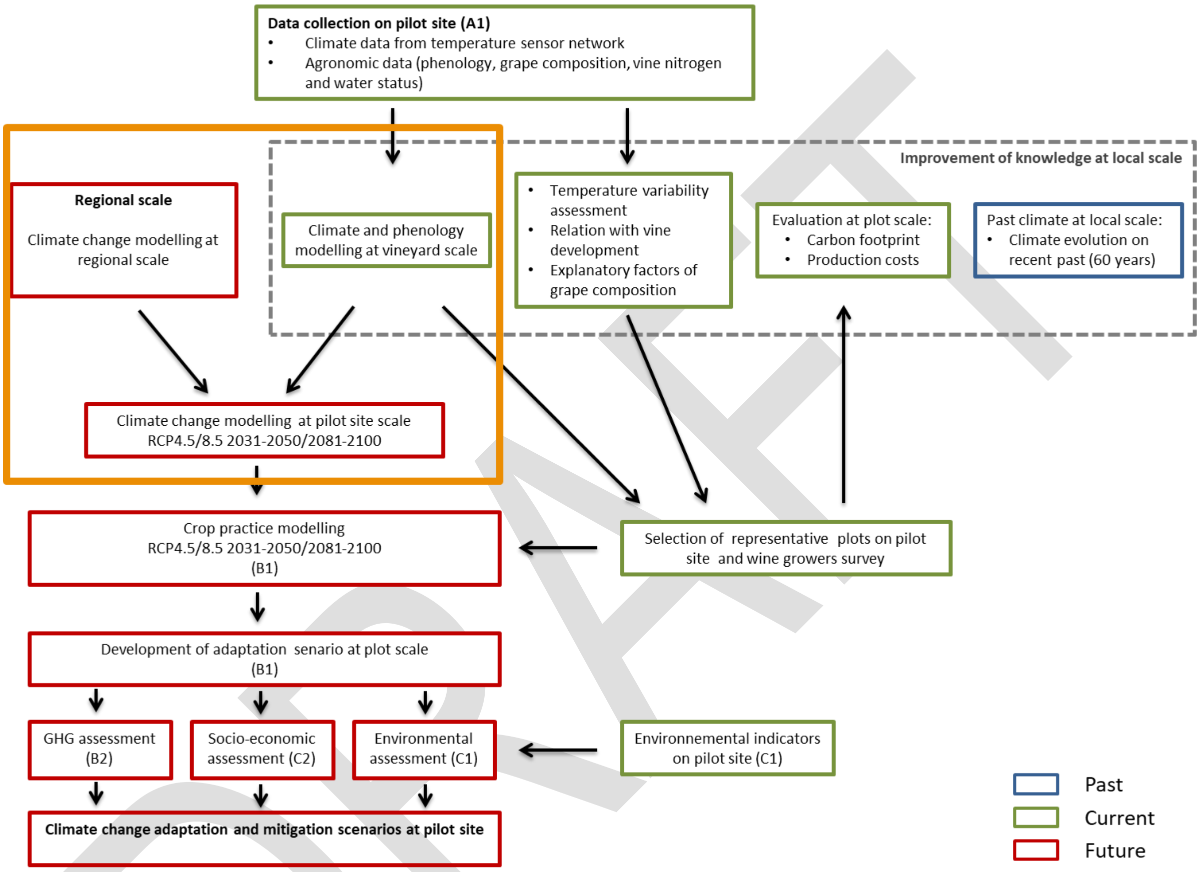


Figure 10: Schematic synthesis of Part 1 of this report

This innovative study, using a relatively small area, illustrates the significant temperature range that was found on this pilot site, and enables a greater understanding of the terroir's potential. The bioclimatic indices and phenological maps allow us to visualise the climatic variability over this territory and their consequences on grapevine development.

These results are valuable decision support tools, enabling vinegrowers to better adapt plant material and vineyard management practices to terroir components. The models generated from this part of the report will be used to generate maps of climate change at field level.

PART 2: MODELLING OF CLIMATE CHANGE EFFECTS AT THE VINEYARD SCALE



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The first part of this report investigated the current climate and its influence on vine development and grape composition; climate and phenological models were developed. In this second part, future climate change indicators were calculated from data of regional climate models (RCM). By coupling the RCM data at a regional scale to the geostatistical climate and phenological models developed at a local scale, production of temperature and phenological maps for future climate change scenarios at vineyard scale became possible.

2.1 Regional approach to climate change modelling

Climate change impacts were analysed for the ADVICLIM pilot sites using an ensemble of RCMs from the EURO-CORDEX high resolution climate change projections (Jacob et al., 2014). Future daily temperature data were extrapolated from RCMs for the greenhouse gas concentration scenarios RCP 4.5 and RCP 8.5 and approx. 12.5 km grid resolution over the period 2020-2100, by averaging the data of the ensemble of climate models. Data of the same ensemble from 1986-2005 were used to describe the (historical) reference climate. The Huglin-Index and the phenological stages mid-flowering and veraison were used as climate change indicators and were calculated for each year, and subsequently averaged out over the periods 1986-2005, 2031-2050 and 2081-2100 (Figure 11). The results for the medium scenario RCP 4.5 and the pessimistic (business as usual) scenario RCP 8.5 were analysed in order to project a realistic bandwidth of changes for these indicators.

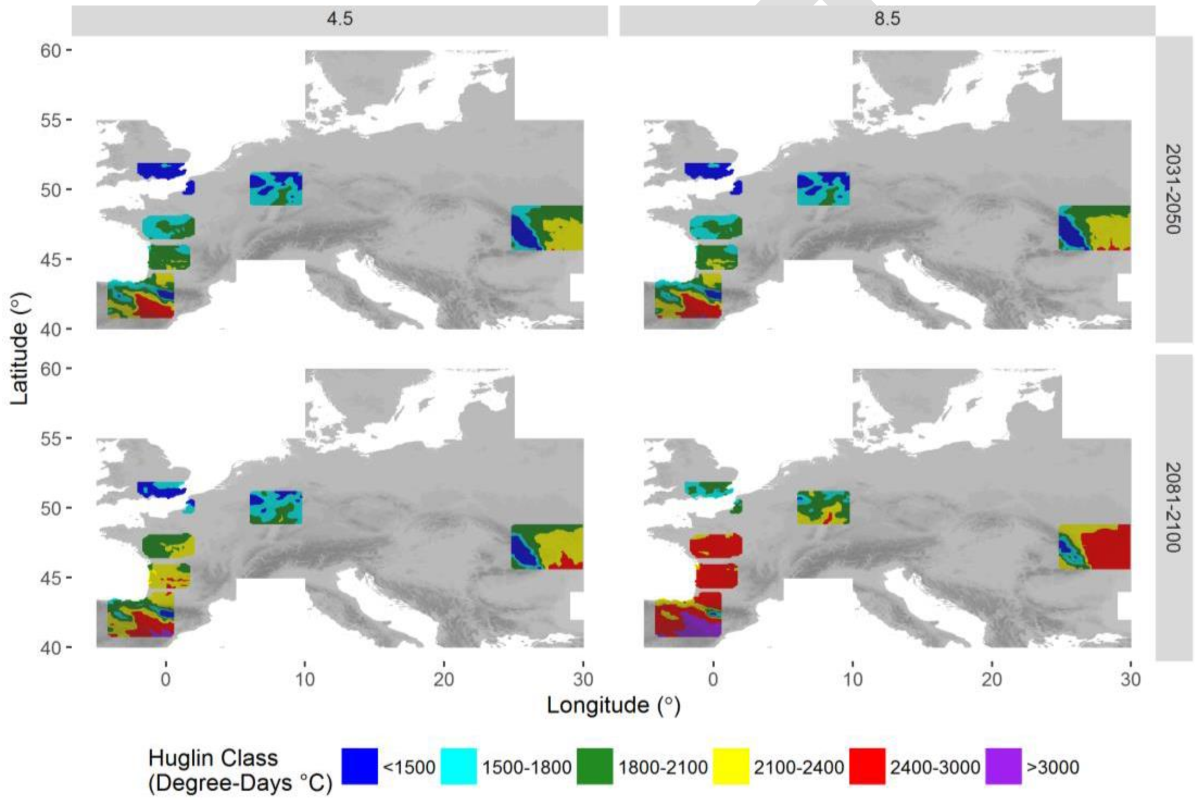


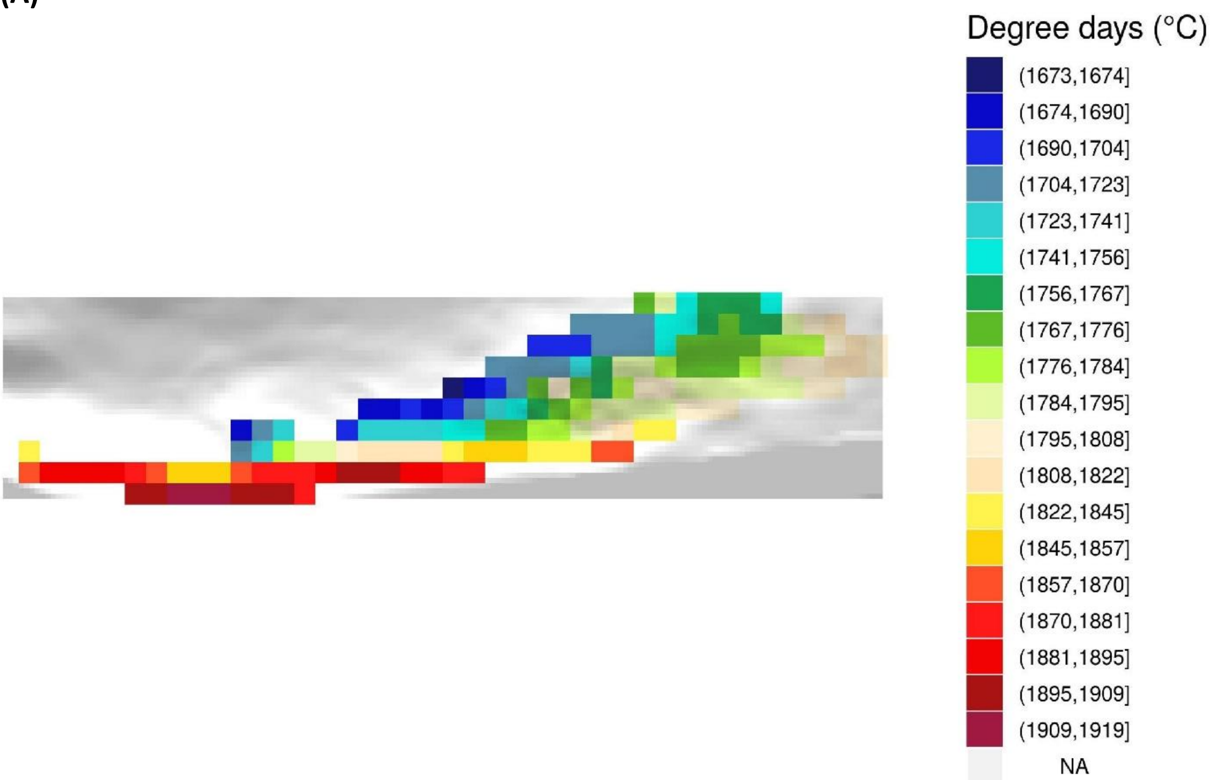
Figure 11: Expected changes in the Huglin-Index for the period 2031 to 2050 and 2081 to 2100 according to the climate scenarios of RCP 4.5 and RCP 8.5. (Data source: EURO-CORDEX).

2.2 Vineyard scale approach to climate change modelling

In order to downscale the RCMs (grid resolution approx.. 12.5 km) to the pilot site scale (grid resolution 30 m or smaller, depending on the digital elevation model available), the geostatistical model outlined in the previous part of this report (Le Roux et al., 2018) was combined with the time series extracted from RCM data. This made it possible to model spatial temperature distributions within the pilot site, which is specified by the temporal temperature developments projected by RCMs. In the next step, maps for the Huglin-Index and dates for mid-flowering and veraison for the reference period 1986-2005 and the projected changes for the periods 2031-2050 and 2081-2100 were produced for both scenarios, RCP 4.5 and RCP 8.5.

Figure 12 represents the evolution of the Huglin-Index, comparing the historical period 1986-2005 in the Rüdesheim pilot site to future periods and climate scenarios.

(A)



(B)

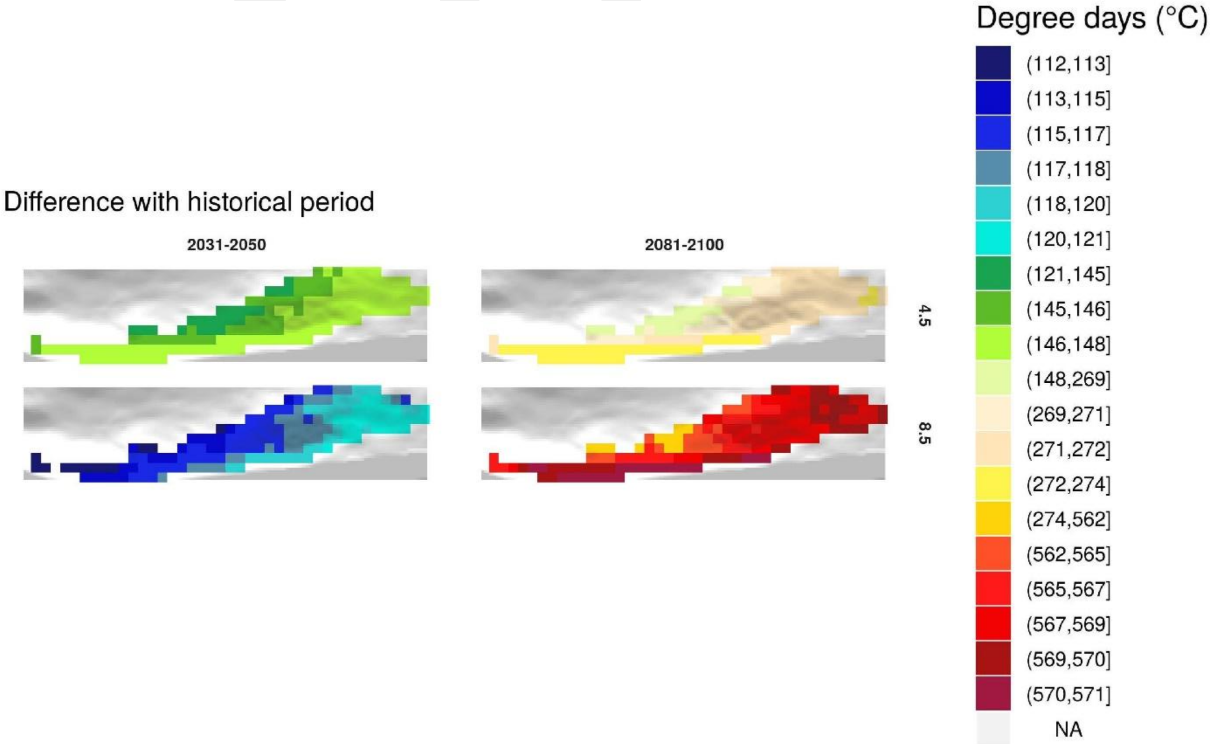


Figure 12: Maps of the Huglin-Index over the Rüdesheim pilot site for the period 1986 to 2005 (A) and expected changes in the Huglin Index (B) for the period 2031 to 2050 and 2081 to 2100 according to the climate scenarios RCP 4.5 and RCP 8.5.

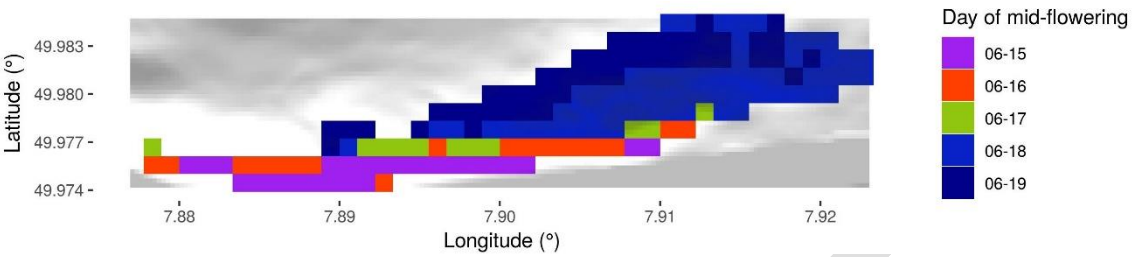
The results of the geostatistical model indicate that the spatial patterns of the Huglin-Index will not change in the future, regardless of the time period or the climate scenario. For both time periods and RCPs projected differences within the region were smaller than 10 degree days (corresponding to one day) and were therefore not detectable. That result is expectable, because temperature differences for Rüdesheim are mostly an effect of the terrain features like elevation and slope, which will not change in future. The warmest areas near the Rhine River will remain the warmest, and the colder areas near the forest will remain comparable cold.

The absolute changes for the near future (2031-2050) and both GHG concentration scenarios are with 120 (RCP 8.5) and 140 degree days (RCP 4.5) comparable. For the background of an observed variability from year-to-year of the Huglin-Index of approx. ±160 (standard deviation, data from Geisenheim from 2000-2019) this means a substantial shift of the distribution to warmer conditions and an increased probability for the occurrence of extreme hot years. Strong differences between the business-as-usual scenario RCP 8.5 and the medium scenario RCP 4.5 emerge at the end of the century (2081-2100). For RCP 4.5, an increase of the Huglin-Index of 270 is projected, this means every second year in this period will be warmer than the warmest year of Geisenheim from 2000-2019. For the business-as-usual scenario RCP 8.5 the Huglin-Index could increase about 570. If the variability from year-to-year remains stable in future, this means that the extreme cold years in this period are in the range of the present extreme hot years, or that approx. 19 of the 20 years from 2081-2100 will be distinctly warmer than every year since data recording started in Geisenheim in 1884.

2.3 Phenology modelling at the vineyard scale in a climate change context

The same fine scale temperature distribution used to map the Huglin-Index was in combination with the Grapevine Flowering and Veraison model (GFV) (Parker et al. 2011, 2013) used to produce maps of the phenological stages flowering and veraison for the variety Riesling (Figure 13 and 14). The map of the reference data from 1986-2005 shows that the early areas near the Rhine River are four days ahead compared to the higher cold areas. This range is lower than the observed one, because the GFV model reduces variability compared to observations. The period for the achievement of veraison in the region is with 14 days longer and the spatial pattern is more realistic, because the temperature summation for the GFV model diverge stronger as the year progresses. The mean value for the modelled veraison (around 23th of August) is only a week later compared to observed values. This acceptable bias is likely a result of the difference between the RCM data (representing spatial means of grid boxes) and the real temperature in the vineyards (which belong to the warmest areas of those grid boxes). The climate projections show, likewise to the maps for the Huglin-Index, that the spatial patterns will to not change in future. For the near future, the earlier development is for both phenological stages and both climate scenarios (RCP 4.5 and RCP 8.5) quite similar (4-8 days). But for the period from 2081-2100 the projections diverge stronger for the two greenhouse gas concentration scenarios. The stage full-bloom will emerge around one week earlier for RCP 4.5 and two weeks for RCP 8.5 and veraison would be about two weeks earlier for RCP 4.5 and more than three weeks for RCP 8.5.

(A)



(B)

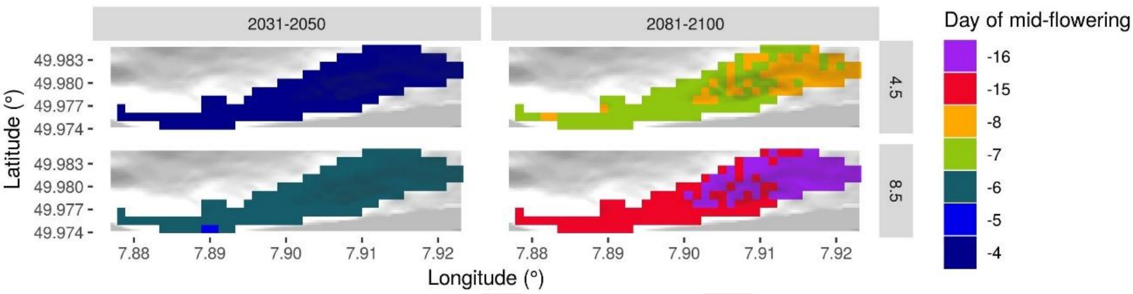
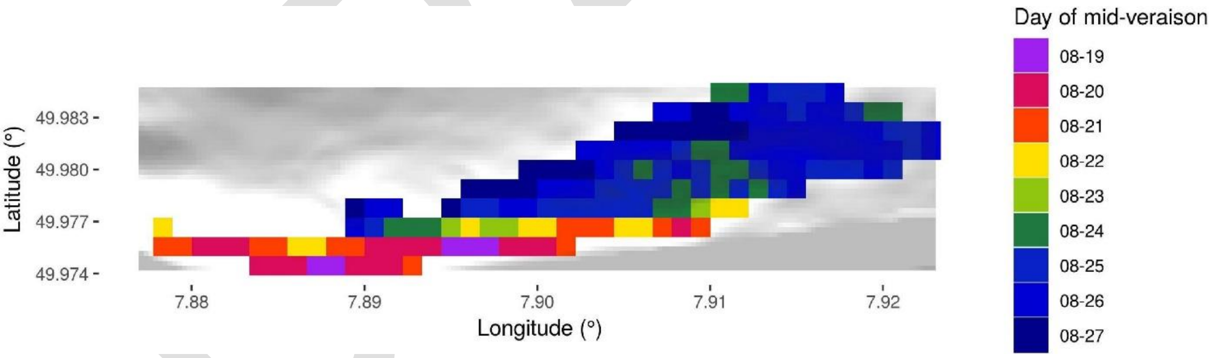


Figure 13: (A): Simulated timing of mid-flowering (full bloom) for Riesling in the Rüdesheim area based on RCM data from 1986-2005 and the GFV phenology model (Parker et al., 2013; legend: month-calendar day). (B): Projections of the incidence of flowering for the periods 2031-2050 and 2081-2100 and the climate scenarios RCP 4.5 an RCP 8.5 relative to 1986-2005.

(A)



(B)

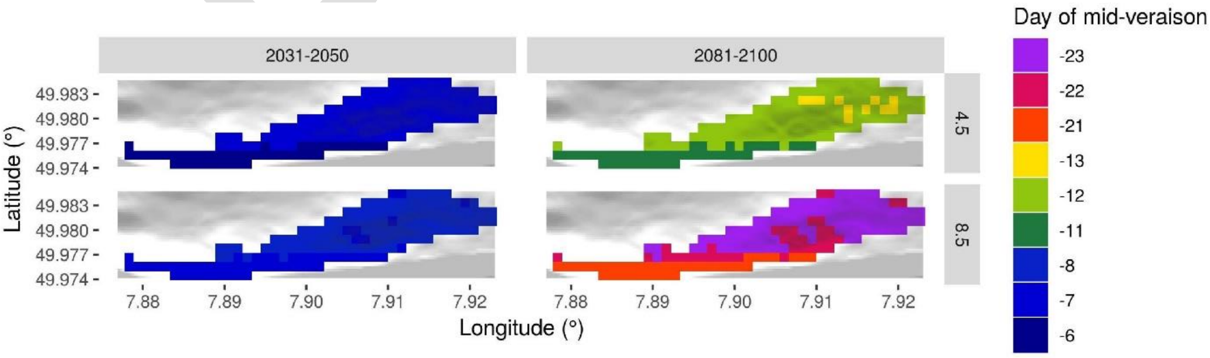


Figure 14: (A): Simulated timing of veraison (begin of ripening) for Riesling in the Rüdesheim area based on RCM data from 1986-2005 and the GFV phenology model (Parker et al., 2013; legend:

month-calendar day). (B): Projections of the timing of veraison for the periods 2031-2050 and 2081-2100 and the climate scenarios RCP 4.5 an RCP 8.5 relative to 1986-2005.

Conclusion part 2

Using a geostatistical modelling approach, spatial temperature patterns were downscaled and maps of relevant climate change indicators at the vineyard scale were produced.

This showed that observed spatial patterns of the distribution of temperature in the pilot site (and corresponding distribution of bioclimatic indices as well as the mostly temperature depending phenology development of the grapevines) will not change in future, which can be explained by the fact that the most important terrain feature impacting on temperature in the Rüdesheim pilot site is the elevation profile.

The results indicated further, that ongoing warming will even in the near future distinctly change the growing conditions for grapevines. The phenological development will be around 4-8 days earlier. Following the projected increase of the Huglin-Index, most of the years in the near future can be classified to the temperate or temperate warm climate class. The viticulture in the Rheingau, located at the 50th degree latitude, and still at the northern fringe of economically important winegrowing in Europe, is currently or historically known as a cool climate winegrowing region, but this statement will cease to apply in future with the progress of climate change.

The projections for the time period at the end of the century showed that these developments will strengthen but diverge clearly depending on the future development of the concentration of greenhouse gases. For RCP 4.5 the stage full-bloom will be one week earlier and veraison two weeks but even one additional week earlier for RCP 8.5. Following the classification of the Huglin-Index, half of the years for RCP 4.5 will be in the range the present climate and the other half warmer than the warmest year since at least 1884, but for RCP 8.5, years in the range of the present climate will more or less no longer exist. Such a strong shift of the conditions of the climate and the environment in a comparable small time period will put an enormous pressure on the ecosystems and because of the close linkage between economy and ecology in agriculture, it is questionable to what extent adaption measures have the potential to take effects. This highlights clearly the benefit of greenhouse gas mitigation actions.

The next step will be to evaluate the consequences of climate change on cultural practices, by using selected plots, which are representative of this pilot site in terms of environment, climate, wine production and cultural practices.

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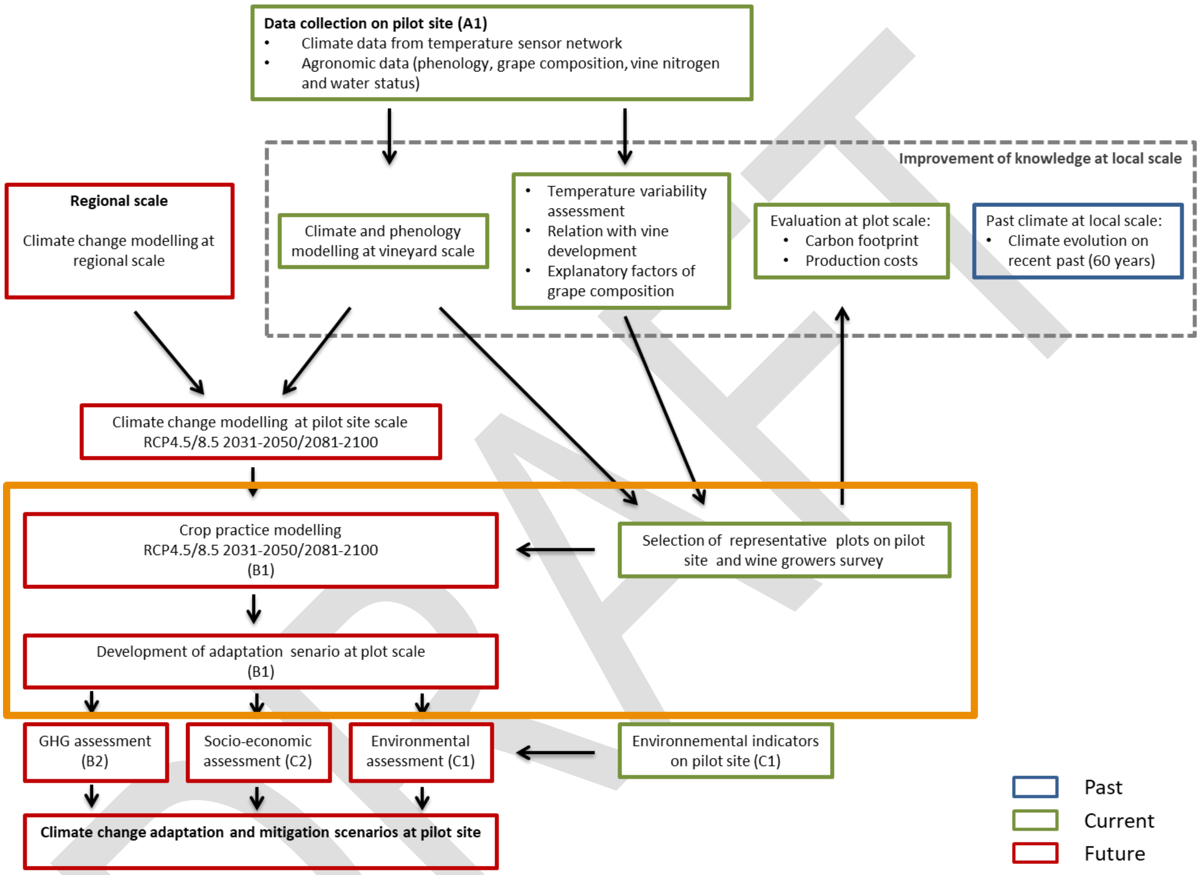
PART 3: ADAPTATION OF CULTURAL PRACTICES TO CLIMATE CHANGE



This part of the report deals with crop husbandry modelling and the development of climate change adaptation practices at the vineyard plot scale. The crop management practices implemented in 2016 were identified for five representative plots in the Rüdesheim pilot site. The objective of this part is to show trends in the timing of phenological stages and to analyse changes in agronomic practices by comparing a set of representative plots. Based on this information, possible changes in practices according to different climate scenarios can be assessed.

3.1 Representative plots characteristics

For the analysis with the SEVE model (Simulating Environmental impacts on Viticultural Ecosystems) five representative plots, equipped with temperature sensor were selected from the pilot site. With the exception of minimal pruning systems, the cultivation of the plots in the Rheingau is quite similar. For soil cultivation the use of alternating systems (one row with cover crops /one row bare) is quite common and a compromise between the positive effects of cover crops (biodiversity, humus preservation, erosion protection, reduction of nitrate leaching) and the negative effects, mainly the competition for nutrients and water, because annual precipitation in the region is with 543 mm (Table 1) comparable low. Differences can be found in the row spacings (old vineyards are planted with smaller row spacings around 1,60 m, younger vineyards in the range of 1,80-2,00 m) and in the choice of plant protection agents (organic or conventional), both play a minor role in terms of adaptation measures to climate change. Therefore, the different altitude of the plots was the main criteria for the plot selection, in order to cover the different temperature conditions of the region.

Figure 15 shows the localisation of the pilot site and the selected plots of the Rüdesheim pilot site. The altitudes of the selected plots vary from 99 to 254 metres, which is representative of the pilot site (80 to 280 metres) and the climatic conditions.

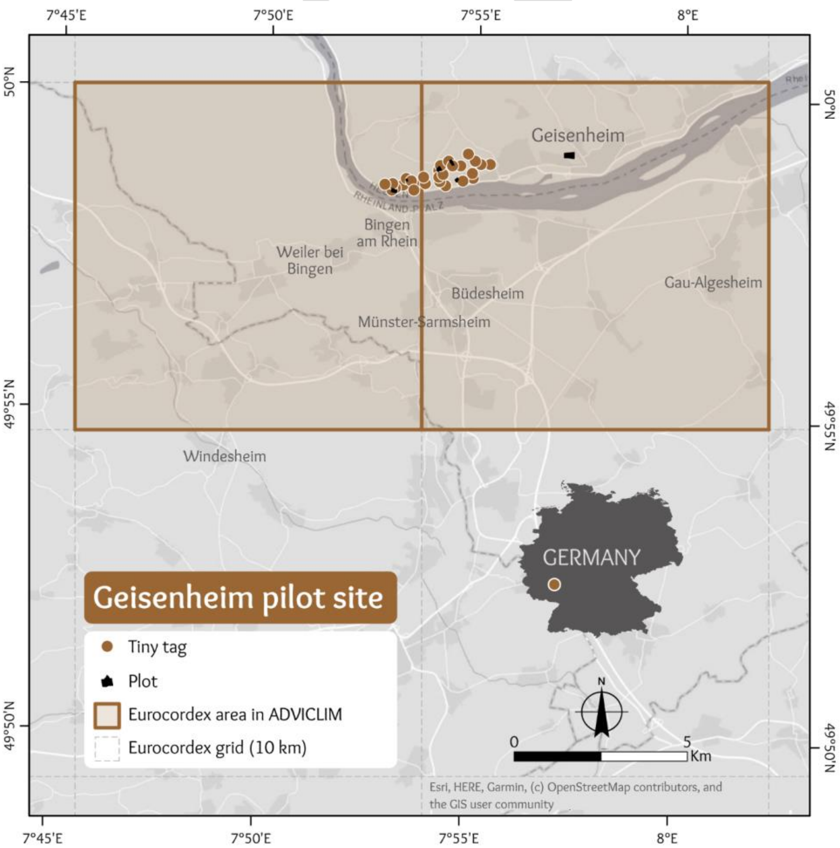


Figure 15: Plots and temperature sensors in the Rüdesheim pilot site

3.2 The SEVE model prototype

In order to assess potential future adaptation trends, a specific prototype of the SEVE model (Simulating Environmental impacts on Viticultural Ecosystems; Tissot et al. (2014)) was implemented in the five representative plots. The baseline of SEVE model was adapted to local constraints and the agronomic characteristic of the Rüdesheim vineyards, with respect to the most common production aims and cultivation methods. For water balance assessment, the model of Hofmann et al. (2014) was used, which is adapted to steep slopes and was validated in vineyards of the pilot site.

3.2.1 Phenological cycle and agronomic action modelling

The results of the modelling of phenological cycles are comparable to those reported in Part 1 and Part 2. The changes in the timing of phenological stages reflect a significant evolution between the first (2031-2050) and the second period (2081-2100), particularly for the scenario RCP 8.5.

The main agronomic actions in the Rüdesheim pilot site are quite similar in the region. Different nutrient and water supply of individual plots and different grower's preferences may influence the timing and frequency of measures like summer pruning, soil cultivation, defoliation, or yield regulations. In this context, the SEVE model tends to underestimate agronomic actions, because the baseline model comprises more standardized practices and not the complete variability observable in the vineyards of Rüdesheim.

3.2.2 Analysis of the differences between plots

The analysis of the five plots showed that different temperature conditions caused by the strong altitude differences were the main factor. The plot were therefore grouped to three classes, the early (warm), medium and late (cooler) plots.

Using these results, model calculations were performed for a typical plot for each group and further studied.

3.2.3 In-depth analysis of the representative plots

In the first approach, the data on the evolution of the phenological stage timings was analysed to evaluate the differences between the two time periods, 2031-2050 and 2081-2100. These results (Table 3) present minimum, median and maximum date of maturity when the model simulates the achievement of 220 g/L sugar content of the must (≈ 13 Vol% alcohol of a dry wine) for each scenario for the variety Riesling. Significant change can be noticed in the timing of the main phenological stages, reflecting an earlier maturation of the grapevine berries in the later periods, especially during the period 2081-2100 for the scenario RCP 8.5. Maturation date for the Riesling variety could advance until mid-August (median) for the early plots.

Differences of maturity date can be detected between all the plots, with variability from 6 to 8 days between the earlier and the latest plots for each scenario. The model is reducing the variability inside the pilot site and selected plots are not representing exactly the extreme values of this area. Year-to-year variability (expressed by the time span between earliest (min) and latest (max) maturation dates of 20-year periods) showed no changes between climate scenarios or time periods.

Table 3: Mean of maturity date minimum, maximum and average for each group of plot

Maturity of Riesling (220 g/l of sugar content of the must)							
		RCP 4.5			RCP 8.5		
		min	median	max	min	median	max
2031-2050	early	28-Aug	07-Sep	15-Sep	31-Aug	07-Sep	16-Sep
	medium	02-Sep	12-Sep	21-Sep	06-Sep	11-Sep	22-Sep
	late	05-Sep	15-Sep	25-Sep	09-Sep	15-Sep	26-Sep
2081-2100	early	20-Aug	01-Sep	10-Sep	11-Aug	18-Aug	28-Aug
	medium	24-Aug	06-Sep	15-Sep	14-Aug	22-Aug	01-Sep
	late	26-Aug	09-Sep	19-Sep	15-Aug	24-Aug	04-Sep

Then, the agronomic intervention workflow, simulated by the SEVE model, was analysed. The agronomic actions are fairly close between the two periods and the two climate scenarios. The number of fungicide treatments are close due to the production method used (conventional on all plots) and the type of product used (systemic treatment product). Also, regarding soil management actions, the SEVE model does not show any significant change in the two RCP scenarios. This also in future unchanged agronomic workflow can be explained by the adaptation potential of the Riesling grape variety to the projected warmer conditions. Moreover, the treatment frequencies of both interventions (fungicide application and soil management) depend also largely on rainfall patterns, whose future projections show a high bandwidth, partly related to the natural climate variability. Therefore, the results concerning the treatment frequencies should be considered with caution due to the high uncertainty of the rainfall projections.

The variability in the number of actions is more visible on an annual scale (from 19 to 28 actions per year).

3.2.4 Potential adaptation scenarios

Potential adaptation scenarios were first defined according to vineyard characteristics and current agronomic practices.

3.2.4.1 Grapevine variety

These scenarios have been implemented in the SEVE model as decision rules; for example, adaptations in winemaking techniques can be used as long as the limit of vine variety adaptation is not reached. Regarding adaptation through the choice of plant material, several parameters are used, such as maturity date in previous years, the age of the vine, and the vine variety permitted in the wine-producing area for the production of quality wine. To define the date of replacement for grape variety, the threshold was set at 4 years /10 where theoretical maturity (220 g/L sugar) has been reached before 23rd of August. Table 4 shows the recommendations (according to the SEVE model) for the conversion of grape varieties for the three test plots. Based on these criteria, changing grapevine varieties might become only a topic at the end of the century for the business-as-usual climate scenario RCP 8.5. But growing Riesling under those conditions would definitely result in a different wine style and typicity. Currently, Riesling is harvested not before mid-September in warm years and on the earliest plots. Harvest times beginning in the second half of September until mid-October are usual. The temperature regime during ripening period (between veraison and maturity), largely in August for the projected conditions, would be much higher compared to current conditions because of a strong increase of temperature by climate change additionally fortified by the

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earlier time period during the year (Table 3). This would probably result in a strong degradation of malic acid resulting to unbalanced wines with low acidity and high in alcohol. If this could be compensated with oenological measures like acidification, is questionable. Therefore, with this criteria, the resulting replacement date can be considered as the probably longest period for the reasonable cultivation of Riesling under the climate scenario RCP 8.5.

Table 4: Vine varietal changes recommended on the selected plots for the climate scenario RCP 8.5

Plot group	Date of replacement	Old grape variety/Huglin-Class	New Huglin-Class
early	2085	Riesling/HI-2	HI-1
medium	2093	Riesling/HI-2	HI-1
late	2097	Riesling/HI-2	HI-1

3.2.4.2 Water balance

The Rüdesheim pilot site is a typical example of a steep slope region where the available water capacity (AWC) of the soils very heterogeneous and the proportion of vineyards with a low AWC is quite high (Löhnertz et al., 2004). Although there is no trend of precipitation observable in the recent past, the frequency and severity of drought stress has increased because of an increasing trend of potential evapotranspiration. Figure 16 shows the simulated number of drought stress for the year 2018, where the water supply was quite well until mid-June but was followed then by a long lasting dry spell and very warm weather conditions, leading to long period of severe drought stress for many vineyards of the region. Many vineyards more or less stopped to accumulate sugar, so that the plots at the cooler places but with better water supply had higher sugar levels. Severe drought stress is negative for quality and yield especially for white varieties, like the traditionally grown Riesling. The future risk for the occurrence of drought stress is not quite clear, because regional climate model project a high bandwidth of precipitation changes for the region, ranging from a decrease to an increase or projected seasonal shifts in form of increasing precipitation in winter but decreasing summer rainfall. Also the precipitation variability might change in future, as well as the frequencies of heat waves. Currently, a few vineyards in the Rüdesheim pilot are already equipped with irrigation systems, but in general establishing the infrastructure for irrigation systems in steep slope regions can be costly and elaborate (Hofmann and Schultz, 2016).

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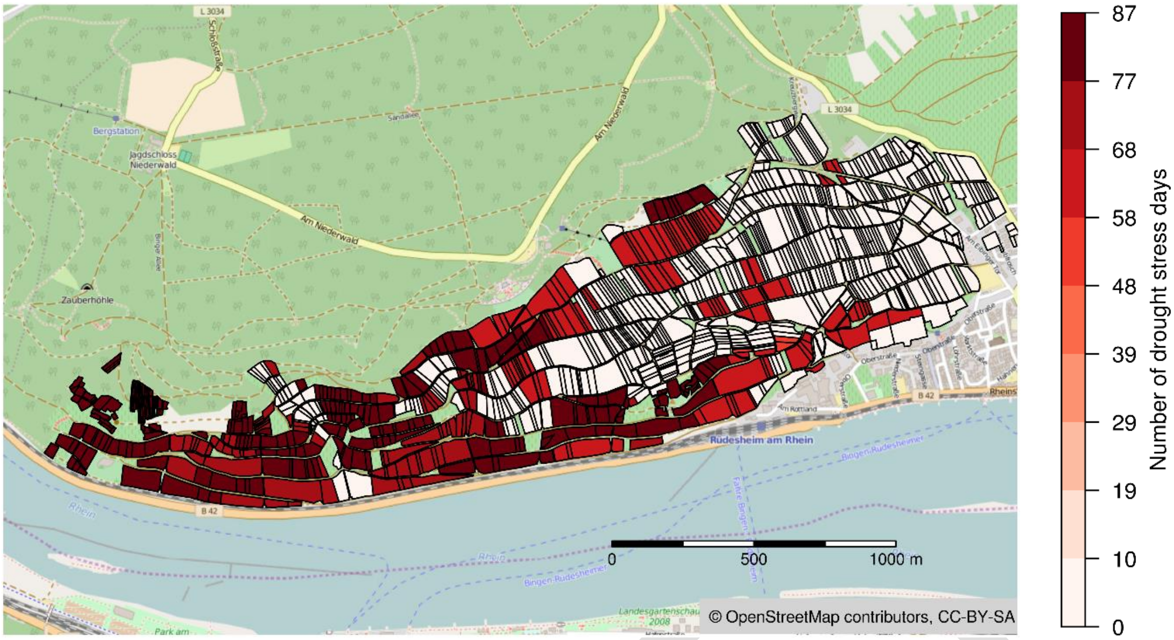

Figure 16: Number of drought stress days from 1th May to 30th September for the year 2018 of the Rüdesheim (Rheingau) pilot site, simulated with a water balance model, based on digital soil maps (HLNUG 2008) and recorded weather data.

3.2.5 Frost risk

Severe spring frost event did not occur for the last 30 years in the Rüdesheim pilot site. This could be an effect of the river as well as the slope of the region, allowing the cold air to drain off from the bottom of the hill. But in the future, this climatic event can be more frequent with climate change. The more early plant development will increase the frost risk, but the increase of temperature could decrease the frost risk.

The model has evaluated frost risk occurrence in the future when negative temperature are recorded during budburst. Results are quite similar for all plots. Table 5 shows a slight increase of the frost risk during the period 2081-2100 were on some plots frost might occur for one year of the twenty year period for the scenario RCP 4.5. For the period 2031-2050 0 years of frost were recorded for both scenarios.

Table 5: Frost risk for the Rüdesheim pilot site, according to SEVE model results for the 2030-2050 and 2080-2100, in the 4.5 and 8.5 scenarios

Scenarios	**2030-2050**	**2080-2100**
RCP 4.5	0	0-1
RCP 8.5	0	0

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Conclusion part 3:

The results presented in this section demonstrate that the SEVE model is able to integrate vinegrowing and agronomic choices and practices with climate variability.

The key findings are:

- Phenology cycle changes are effectively integrated into the SEVE model, with simulation results comparable to outputs provided by the geostatistical model presented in part 2.
- The agronomic interventions are quite similar for all plots and is not projected to change in the near future (2031-2050) and also not at the end of the century (2081-2100), for both climate scenarios.
- The recommended climate change adaptation strategies are the change in grapevine variety during the period from 2081-2100 for the scenario RCP 8.5. The water balance model showed that steep slope part in the west of the region is susceptible for the occurrence of drought stress, with unclear future developments.

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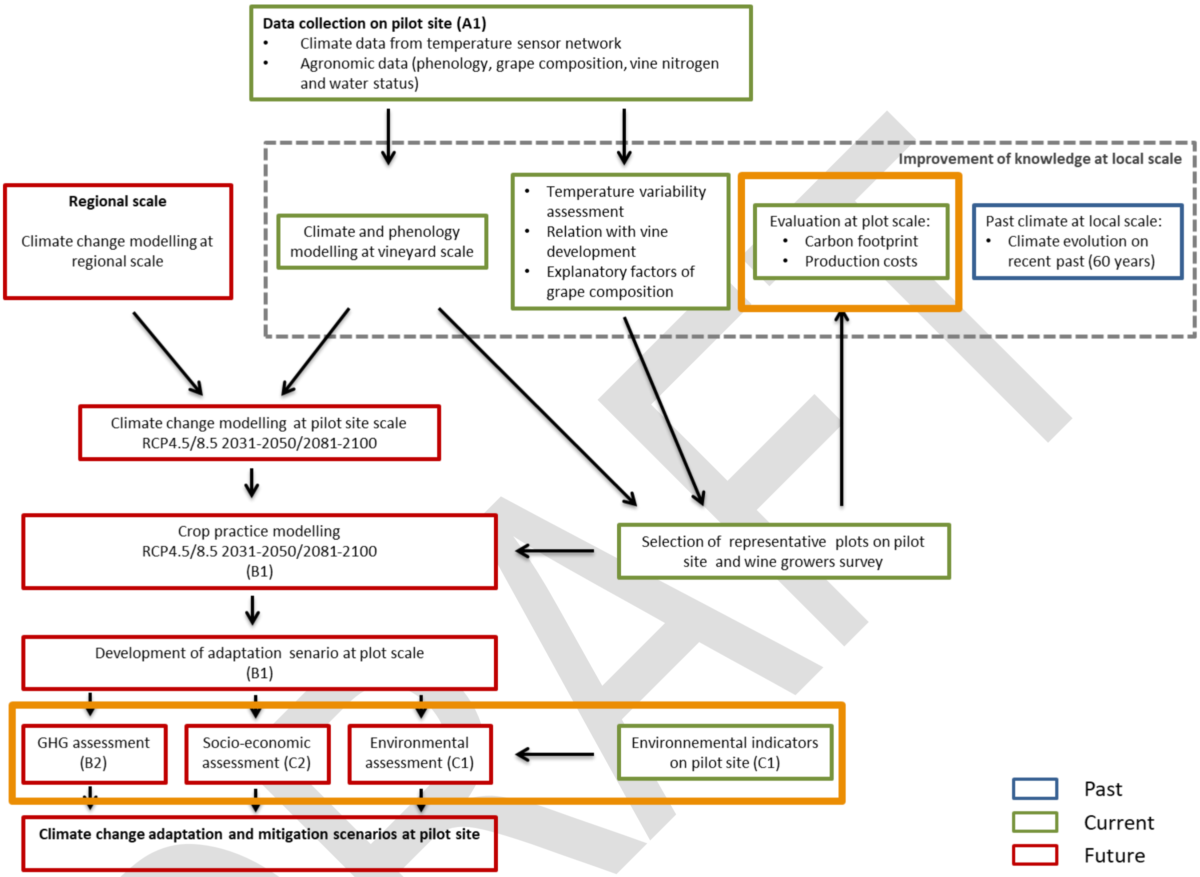
PART 4: SUSTAINABILITY ASSESSMENT OF CURRENT AND FUTURE VITICULTURAL PRACTICES



The preceding part of this report investigated the evolution of viticultural practices on the Rüdesheim pilot site and different viticultural adaptation scenarios. These changes can affect the environmental footprint or the socio-economic conditions of the vinegrowers. The potential impact of these scenarios on the environment and on production costs are discussed in this part of the report. Current environmental indicators at pilot site scale were defined, and greenhouse gas (GHG) emissions and the costs of changes in viticultural practices were calculated. The objective of this part of the report is to inform vinegrowers on the sustainability of their practices, both at the current time and in the future.

4.1 Greenhouse gas emissions assessment

The objective is to evaluate GHG emissions for each current cultural practice on the representative plots. In this report, results were based on cultural practices implemented in 2017 and 2018. GHG emission assessment provides information to winegrowers on the environmental impact of their practices and enables them to evaluate potential mitigation strategies.

4.1.1 Current GHG emissions at plot scale

The GHG emission calculation methodology has been applied for the cultural years 2017-2018, on the representative plots of the Rüdesheim pilot site, monitored for their vineyard practices. Because of the similarity of viticultural practices for most of the pilot site, three typical plots were chosen in order to assess the variability of GHG emissions and to get representative results. All the elements taken into account are listed in the Action B2 deliverable of the project. This methodology was designed to identify:

- the most GHG-emitting management strategy among the sampled plots

- the most GHG-emitting vineyard operations

- the major types of GHG emissions

The accuracy of these calculations allows us to assess potential gains by vinegrowers in terms of GHG attenuation.

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4.1.1.1 GHG emissions per plot

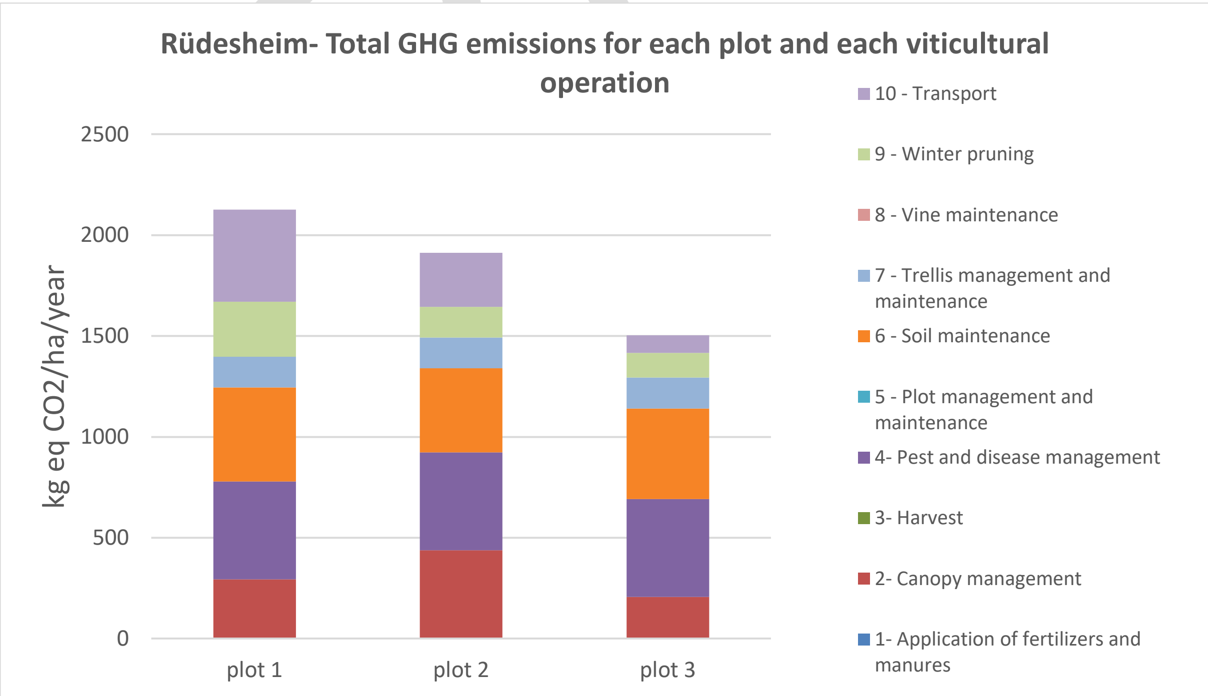


Figure 17: Total GHG emissions for each plot, categorized by viticultural operation

The GHG emissions (Figure 17) for the plots range from 1500 to 2100 kg eq CO2/ha/year. The most emitting interventions are pest and disease management with on average 480 kg eq

CO2/ha/year and soil maintenance with 440 kg eg CO2/ha/year, both together contribute to 50 % of the total GHG emissions. Pest and disease management, soil maintenance and trellis management were performed in the same way on all plots and show similar GHG results. Differences can be found for the more site specific operations, the canopy management winter pruning and transport. The transport differences can be explained by different distances (3-6 km) from the vineyard to the winery. As harvest is performed by hand in the pilot sites the GHG emissions are included in the transport emissions. Application of fertilizers and manures is not performed in every year in the vineyard and also not in the analysed years 2017 and 2018.

4.1.1.2 Direct and indirect emissions

The difference between direct and indirect GHG emissions were calculated for each plot (Figure 18). Direct emissions are those emitted by individual interventions of the grower (causing for example fuel consumption) and indirect emissions are produced during the production and extraction of raw materials and the manufacturing of the system elements. Direct emissions of the vineyards are very close and account for 67 to 72 % of the total emissions of each plot.

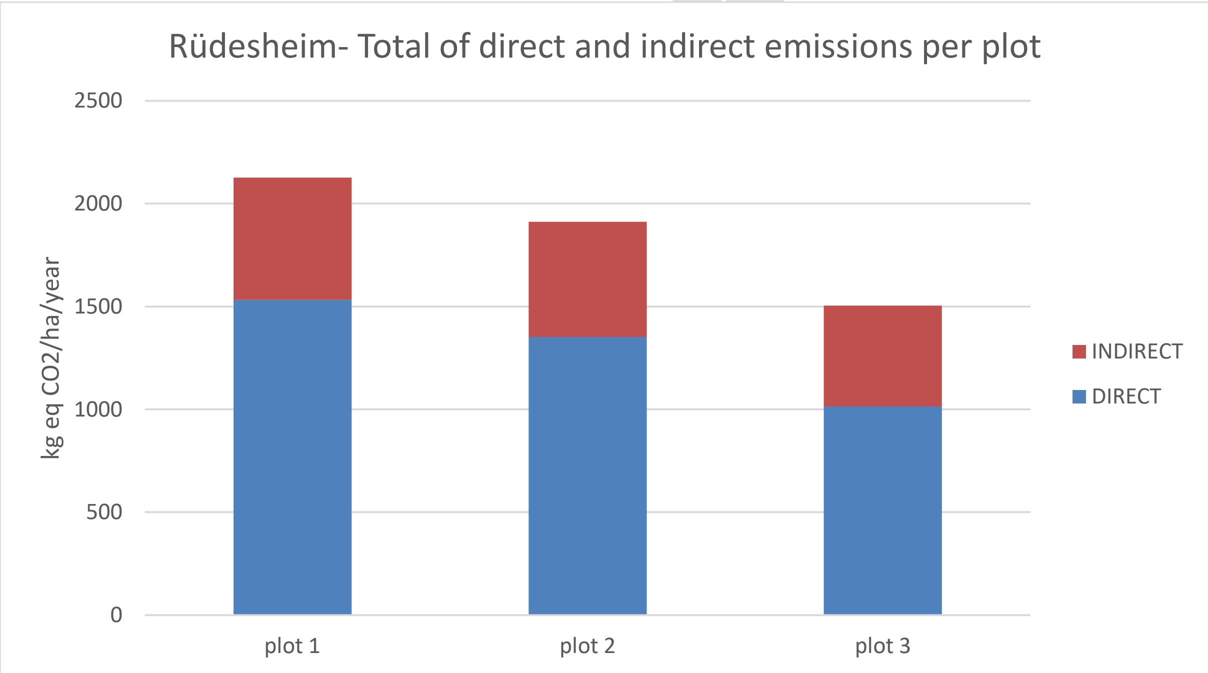
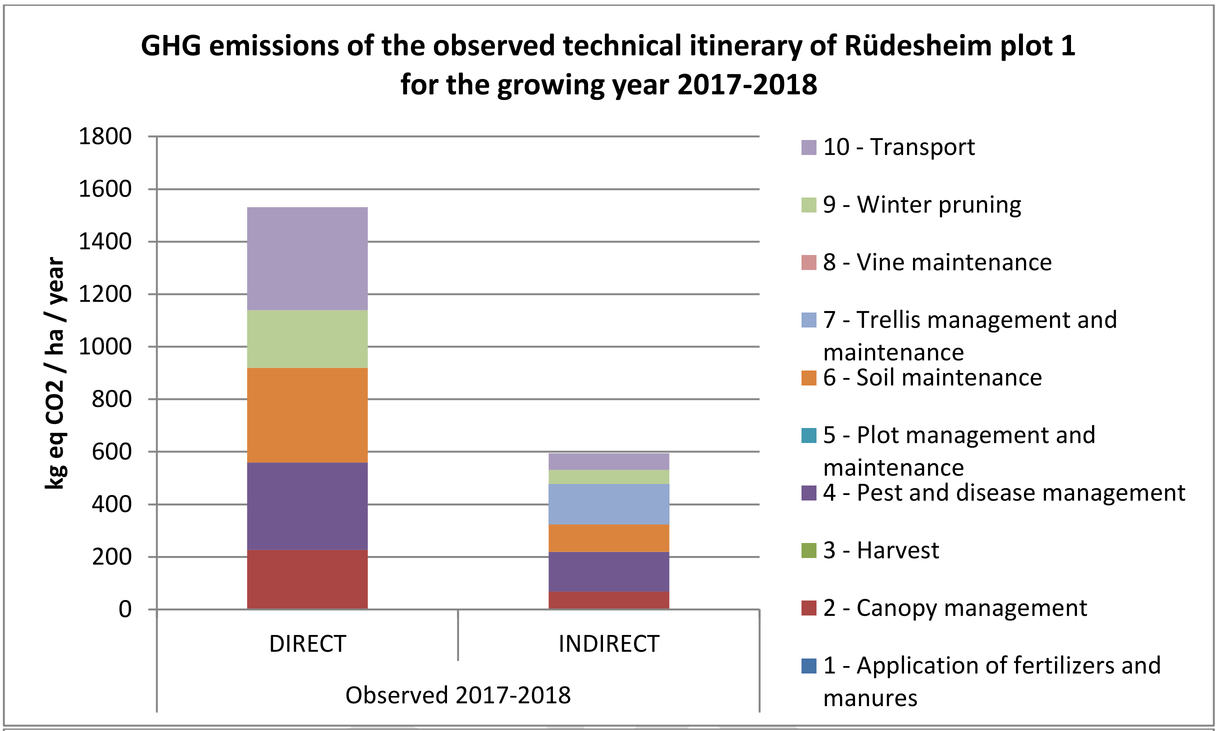


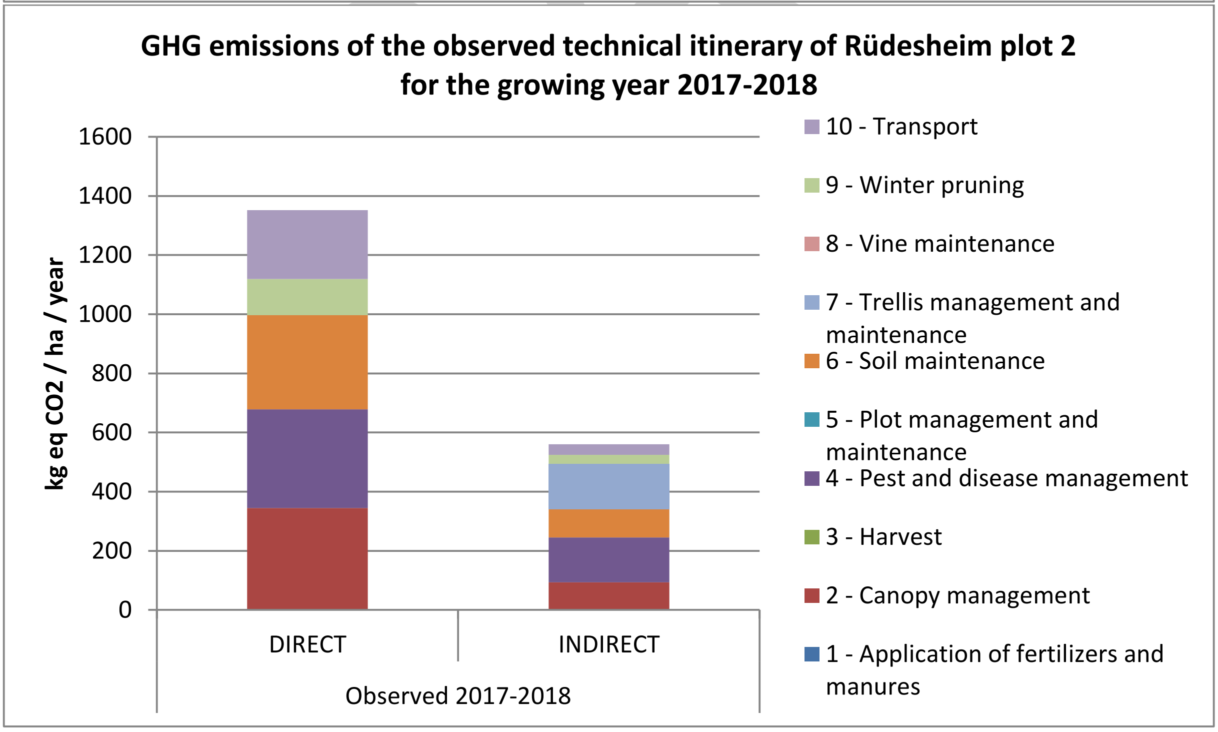
Figure 18: Total direct and indirect emissions per plot

Figure 19 illustrates the GHG emission results for plots 1 (Gr3), 15 (Gr2) and 70 (Gr1), for the growing year 2015-2016.

The split between direct and indirect emissions depends on the vineyard operation. Some vineyard operations, like pest and diseases management or trellis management, involves inputs or equipment that do not themselves produce any GHG emissions in the field, but generate significant indirect emissions.

For the three plots, pest and disease management generates the most direct and indirect GHG emissions. Soil maintenance and transport emits a lot of direct GHG emissions as well. On the other hand, the level of indirect emissions generated by trellising equipment is significant, even after having smoothed the emissions generated by the manufacturing process over the whole lifetime of the machines used.





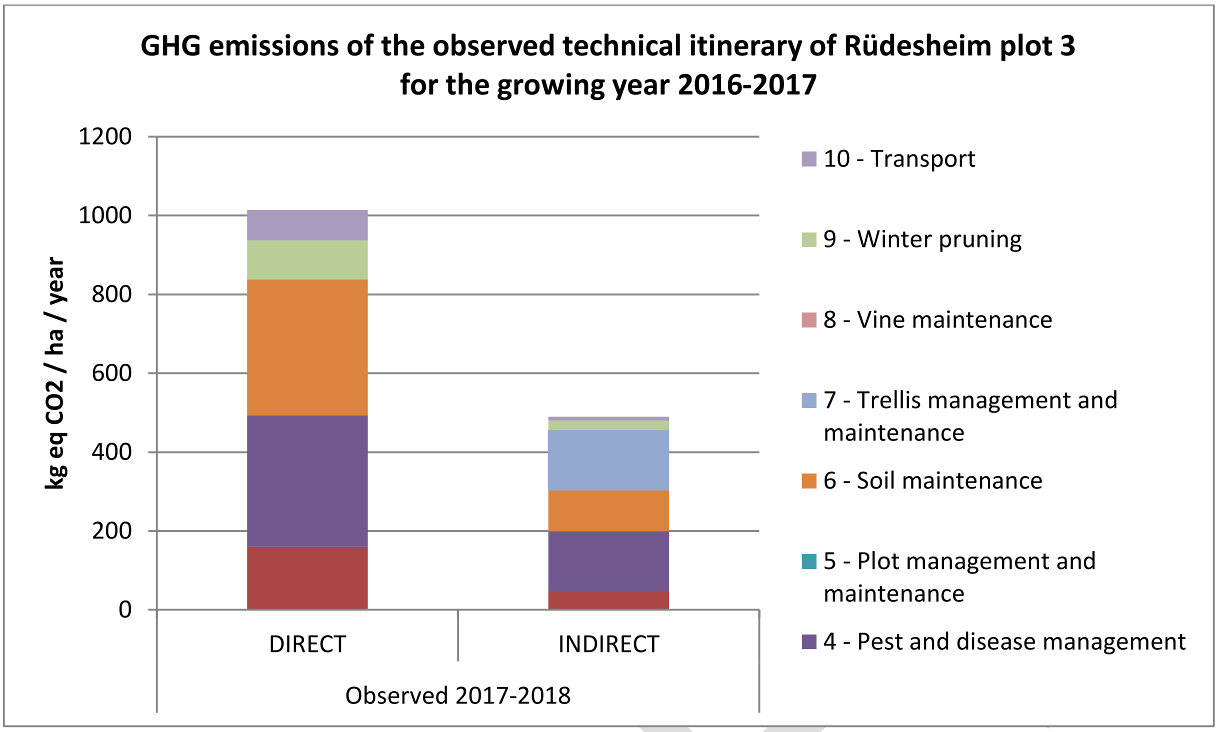


Figure 19: Direct and Indirect GHG emissions assessment by interventions for representative plots in the 2015-16 growing season

4.1.2 Greenhouse gas emissions estimation of adaptation strategies to climate change

4.1.2.1 Methodology for assessing the strategies

As explained in Part 3, the SEVE model produced scenarios describing the evolution of cultural practices (date and number of all the interventions in a season), and some of the possible adaptation strategies. GHG emission levels can vary according to changes in tools and equipment and changes in the quantities of inputs used, particularly pesticides, fertilisers and energy (mostly diesel and electricity).

For the Rüdesheim pilot sites, the SEVE model simulated no significant changes of cultivation practices under future climate conditions. Also the variety Riesling is an already late ripening grapevine variety with a well potential also for warmer conditions. From current observations earlier ripening might result in a decrease of fungicide treatments against powdery and downy mildew, because the plants reach earlier in the season the status, where the grapes are not vulnerable any more. On the other side, earlier ripening means ripening under warmer conditions, which increases the risk for botrytis and other ripe rot occurrences, especially in seasons with high rainfall. This could lead to one or two more applications of fungicides or to an increase in canopy management measures. The GHG emissions are probably more influenced by changes of future technical or cultural developments, like e.g. fungicide applications with drones, mechanical harvesters for steep slopes, detailed weather and disease forecasting systems or a greater dissemination of fungicide resistant varieties. These developments are very diverse and unpredictable as well as their impact on GHG emissions.

4.1.2.2 Results of GHG emissions of scenarios

The results show that potential to reduce GHG emissions by the adaption of cultural practices is fairly low. Also most of the technical developments currently under discussion or developed in the recent years aim to reduce production cost but not to reduce GHG emissions. The ongoing mechanization of cultivation possibilities and the trend to stronger machines with more horse power (like mechanical harvesters) will also lead to an increase of GHG emissions in the future. Significant reductions of GHG emissions can only be expected by a much stronger use of renewable energy instead of fossil fuel in all fields of the industry, which could also reduce the GHG emissions. For this background, the aims of the “European Green Deal” of the European commission to halve GHG emissions as well as the use of pesticides until 2030 or to make Europe climate neutral in 2050 can probably only be reached with a strong paradigm change in the development of new techniques and production methods as well as the associated policies at all levels.

4.2 Environmental assessment

The environmental impact of viticulture is quite complex. Alongside economic profitability, environmental sustainability has become a major factor in world viticulture and current legislation. European grapevine varieties are not resistant against the major fungal diseases powdery and downy mildew, leading to a high number of applications and use of fungicides. Herbicides are often used to manage the vineyard floor, and insecticides are used to control harmful insects. Due to climate change and worldwide trade and exchange, regional shifts in pest occurrences and new pests (such as the spotted wing drosophila) can be observed across Europe. Although disease monitoring and new management technologies have led to a reduction in the use of pesticides, soil management and plant protection measures lead to frequent tractor passes. Furthermore, vinegrowing regions are often monocultures, which have the potential to have negative effects on biodiversity. These observations illustrate that the interactions between viticulture and the environment are diverse. Action C1 has therefore defined several currently important environmental indicators, which can be used to assess and describe in detail these interactions.

4.2.1 Current environmental indicators in Rüdesheim pilot site

4.2.1.1 Water and Water management:

The environmental aspects and objectives of the water management are defined by the EU-Water Framework Directive 2000/60/EC (WFD). The aim of the directive is to achieve or to conserve all water bodies (rivers, lakes, groundwater and coastal water) in a ‘good status’, which means for surface water bodies a good chemical und ecological status, respective ecological potential and for groundwater bodies the good chemical and quantitative status. The concentration of nitrate (NO_{3-}− and NH_{4+}) and pesticides are essential for the assessment of the groundwater status as well as for planning of measures. As agricultural land use could contribute to groundwater contamination, the general objectives of the WFD are important for the viticulture in the Rheingau growing region and should be respected in the development of adaptation and mitigation measures in viticulture (Berthold et al., 2016).

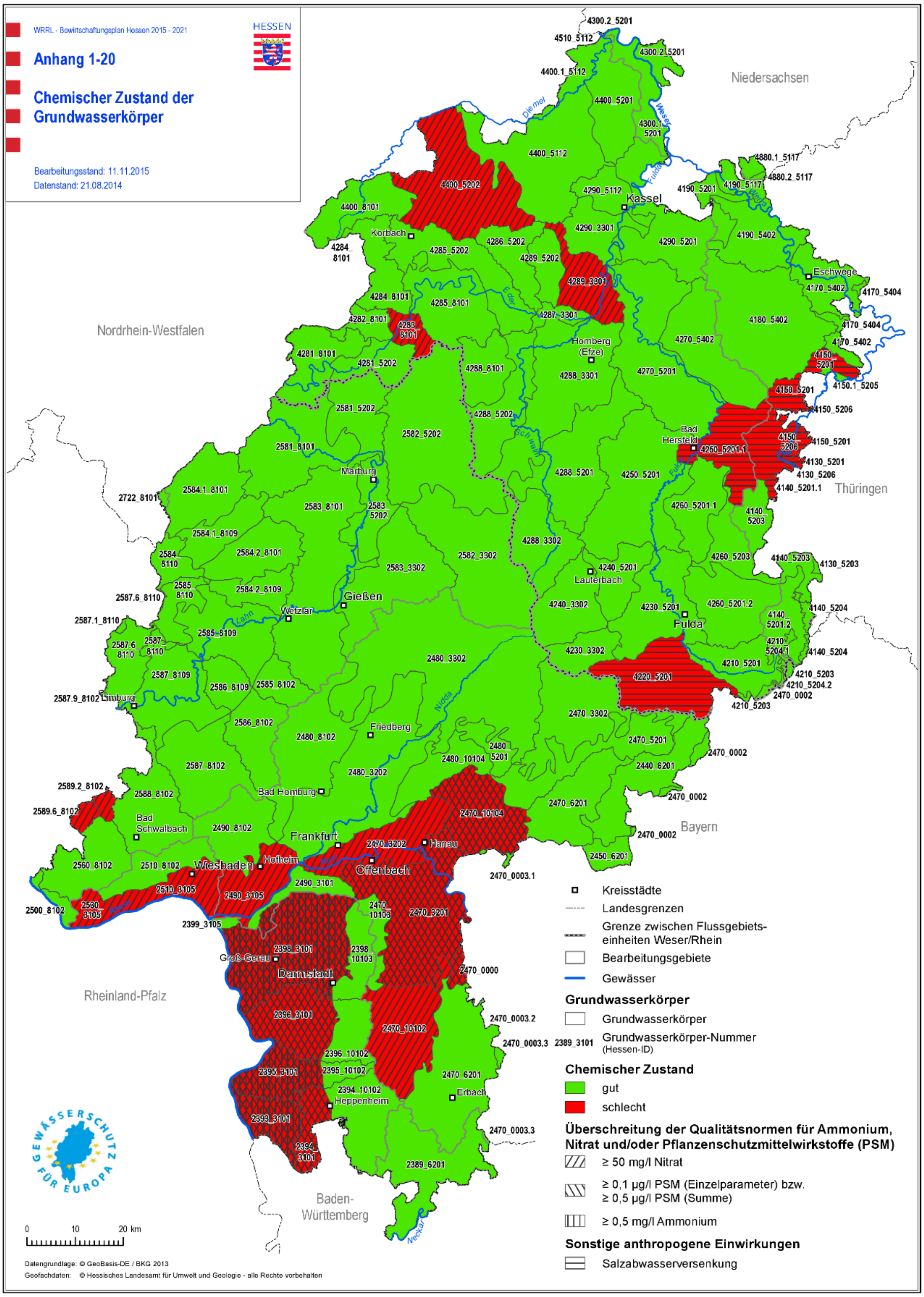


Figure 20 : Chemical condition of the groundwater bodies in the state of Hesse (Germany), classified corresponding to the EU-water framework directive (green is good and red is bad). The winegrowing region is in the region in the west of Wiesbaden and is not in a good status (red), because the groundwater bodies exceed the threshold values for nitrates (≥ 50 mg/L).

Currently, in the state of Hesse, 19 of 127 ground water bodies are in a poor chemical status because of too high concentrations of nitrate or pesticides. Most of the groundwater monitoring sites located in the Rheingau area (in the southwest of Hesse), exceed the threshold of 50 mg/L of nitrate. Thereby, nearly all viticultural land is located in areas which have a high pollution potential for groundwater. Measures to prevent a deterioration or to reach a good status of the groundwater bodies are mainly based on consulting and support programs by the relevant authorities, which are a part of the current management plan for the implementation of the WFD in Hesse. Concerning viticulture, the following points are of great importance for the water protection (Berthold et al., 2016):

- Recommendations concerning the use of mineral of organic fertilizers must respect water protection issues.

- Higher temperatures during winter lead to higher mineralization rates of nitrogen. Nitrate leaching during winter months is considered to be the main source of the nitrate pollution of the groundwater. Due to climate change winter temperatures will increase and climate models project an increase of winter precipitation in the Rheingau, which will also increase the risk of nitrate leaching. An important measure to counteract this increasing risk it the use of specific vegetation during winter months, in order to fixate the mineralized nitrogen by the plants, which is then available for grapevines after soil cultivation in spring.

- Against the background of the WFD avoiding soil erosion is also important for water protection. Most of the Rheingau winegrowing area is oversupplied with phosphate, by the use of mineral complete fertilizers in the past and the low extraction of phosphate by grapevines. Soil erosion transports the topsoil, where nitrogen and phosphate is enriched, to the surface water bodies which contributes mainly to eutrophication of the surface water bodies.

4.2.1.2 Water management

Concerning water management, most of the Rheingau growing region is not prone to water deficit, because of their high water storage capacity. But steep slope regions like the Rüdesheim pilot site have a higher proportion of vineyards with low water holding capacity, facing drought stress in dry years. Drought stress is negative for quality and yield of white varieties, like the traditionally grown Riesling. The risk for drought stress may increase with ongoing climate change in future. Currently, a part of the vineyards in the Rüdesheim pilot site can be irrigated, but in general establishing the infrastructure for irrigation systems in steep slope regions can be costly and elaborate (Hofmann and Schultz, 2016).

4.2.1.3 Waste

Large amounts of wastewater and organic by-products accumulate during the production of grapes and wine, which are in general polluted with carbohydrates, fruit acids, alcohol, organic nitrogen compounds and residues from must, yeast and fining agents and others. In principle, those substrates are readily biodegradable, but wastewater can be seasonally highly concentrated and overload wastewater treatment plants. Organic residues can be composted or directly applied to viticultural land, whereby legal requirements for storage and applying have to be respected. (Schäfer and Jung, 2016).

4.2.1.4 Climate change

Climate change has several impacts on grape production. For the Rüdesheim pilot site, the recent warming had positive effects on quality and quality stability, but also may change the wine style and local typicity of this traditional growing region (Hofmann et al., 2016). Also

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several new risk have emerged in the recent years, which are possibly related to climate change, increased climate variability or new conditions by changed plant (phenology) and weather development. In Rüdesheim pilot site, warm end wet conditions during ripening period (between veraison and harvest) occur more often, by the combined effect of higher temperatures (climate change) and earlier plant development even without a strong change of precipitation patterns (Schultz and Hofmann, 2015). This has increased the risk for botrytis and secondary infections which could lead to grape rot, a reason under discussion for the decrease of yield in the recent years (Figure 21). Some of the recent years showed also an increased risk for downy mildew by much stronger primary (soil borne) infections and/or well conditions for sporulation and secondary infections. Furthermore new pests and diseases like *drosophila suzukii*, black rot (Molitor et al. 2010), black wood disease (vector *hyalesthes obsoletus*) emerge in the recent years and also the dangerous American grapevine leafhopper (vector of *flavescence dorée*) is spreading to north, but still not found in Germany.

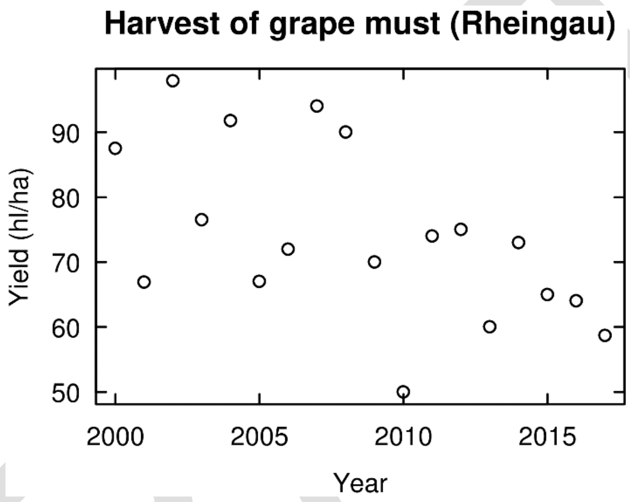

Figure 21: Harvest of grape must for the German winegrowing region Rheingau. Data based on "Deutscher Wein Statistik", published by the German Wine Institute, www.germanwines.de

4.2.1.5 Soil erosion

Cover crops between the rows have shown to be great protection against erosion even for steep slopes and high precipitation intensity but cannot be used for all viticultural land and all management conditions (Löhnertz et al., 2004; Jung and Meilinger, 2016). In steep slope areas the rows are often alternating kept bare or green covered (often by natural vegetation), to keep a balance between the positive effects of vegetation and the water competition for the vines. The bare rows are cultivated at begin of May and then susceptible for erosion until a protecting vegetation has established again (normally during June). Tillage later in the year is normally not recommended, because of the increased risk for erosion and the additional mineralization of nutrients, which could increase the risk for botrytis. Replanted vineyards are by the preceding clearing and tracks of planting machines very vulnerable to soil erosion and should be protected by covering the ground with straw, bank mulch or other materials. Also the area underneath the vines, normally kept bare mechanically or by the use of herbicides, shows often erosion after heavy precipitation events.

4.2.1.6 Soil acidification

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Soil acidification is in general not a problem in the Rheingau. For grapevines slightly acidic to neutral soils (pH 6.0 -7.0) are recommended. In cases of more acidic soils, the pH is regulated by liming.

4.2.1.7 Soil compaction

Soil compaction in vineyards can occur by the frequent driving over the vine rows by tractors or grape harvesters. Soil compaction is an important cause of soil degradation, reducing the pore size, water storage capacity, gas exchange, infiltration rate (enhancing erosion), less root growth, soil life and poor tilth. Cover crops can stabilize the soil and soil loosening can reduce soil compaction but loosed rows should not be used for several months.

4.2.1.8 Biodiversity

Whereas biodiversity is quite limited in flat, clean and uniform growing regions, steep slope regions provide, with their diversified landscape, dry walls, flower strips, embankments, stairs and rock outcrops, natural habitats for a wide range of rare plants and animals (Jäger and Porten, 2018). The Rüdesheim pilot site is part of the Upper Middle Rhine Valley (UNESCO World Heritage), which is also together with the side valleys Nahe and Moselle a biodiversity hotspot region of the Bundesamt für Naturschutz (BfN, federal agency for conservation of nature). The biodiversity in steep slope region, or of special measures in order to conserve steep slope viticulture (like cross-terracing of vineyards instead of the management of down facing row direction) is currently under investigation by research projects (www.bioquis.de).

4.3 Socio-economic assessment

Socio-economic impacts of climate change were assessed for the 3 representative plots of Rüdesheim pilot site, based on the viticultural practices used during the 2016 vintage. Missing values were added by a German reference book (KTBL, 2017). The three plots were chosen to represented different cultivation practices, determined by the different character of the landscape of the pilot site. The plot Wilgert is a typical vineyard of the region with a gentle slope of 27 %, which can be mechanized with a tractor. The vineyard was planted in 1983 with a row distance of 1.60 m. In the recent years the growers moved to wider row spacing of 1.80-2.00 m in order to reduce labor costs (RPDA, 2012) by a reduction of tractor passes. The plot Ehrenfels (planted in 1996) is a very steep slope (70 %) and is too steep to be mechanized by tractors. But in the recent years, due to technical developments, the possibilities for mechanization were much improved by crawler tractors fixed with a rope which can also transport several devices like sprayers or mowing tools, but cannot go as fast as tractors in flat vineyards. The plot Krähennest is an area of small terraces, where only handheld machines can be used in. Terraces were most typical for the region before land consolidation measures in the 1970ties. Rest of those plots became mainly fallows. In the recent years, those plots were partly recultivated with some enthusiastic spirit, because working hours for those plots are often in the range of 1000-1500 hours per year (KTBL, 2017). The Krähennest itself belongs to the winery of the Hochschule Geisenheim and was replanted in 2008. In 2019, students of the Hochschule Geisenheim documented 75 different plant species, which emphasizes the value of those landscape elements for the biodiversity. Beside of minimal pruning systems, which were not part of the project, this three plots represent the most typical cultivation types of the region.

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Table 6: Characteristics of the 3 representative plots in the Geisenheim pilot site

(Alternative = alternating plant cover and bare soil in inter-row)

	ha	Plantation density	Conventional / Organic	Inter rows plant cover surface	Inter vine soil management
Krähennest	0.28	6993	Organic	Entire surface	Mowing and hacking
Wilgert	1.25	5680	Conventional	Alternative	Mechanical weeding
Ehrenfels	1.10	3636	Conventional	Entire surface	Chemical weeding

4.3.1 Current practice costs at the plot scale

4.3.1.1 Total cost by plots

Figure 22 shows the total costs, consistent of labour costs, costs for the used machinery, plant protection products (fungicides) and repair materials but without the costs for land purchase, clearing old plantations and planting and maintenance of a new vineyard. Labour costs due to strong differences of working hours are the main factor explaining the differences of the costs of the three investigated plots of the Rüdesheim pilot site, which are 19.145 €/ha for the plot Krähennest, 13.705 €/ha for the plot Ehrenfels and 6793 €/ha for the plot Wilgert. Pruning is quite similar between all plots, because this working step is least mechanised. It is the most expensive work for the flat plot Wilgert. The biggest difference for all plots is the harvest, which is mechanised for the plot Wilgert, but not for the steep slope Ehrenfels and the terraces of the Krähennest. Canopy management is quite expensive for the plot Krähennest, because it is done by hand and needs a lot of time. Assuming a wine production of 75 hl/ha, the viticultural production cost per litre wine are 2.55 €/L (Krähennest), 1.82 €/L (Ehrenfels) and 0.90 €/L (Wilgert). This numbers are rough estimates, because the yield is often lower in terraces and steep slopes compared to flat vineyards and other cost factors (e.g. accommodation costs for seasonal workers) are not reflected in this cost breakdown.

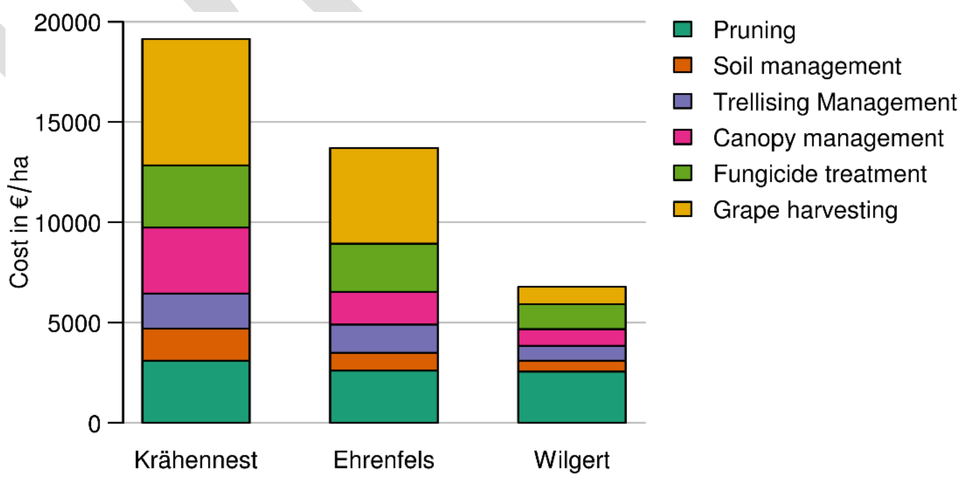

Figure 22 : Cost estimation per ha split up by sub-viticultural operations for three differently cultivated plots in the Rüdesheim pilot site

4.3.2 The socio-economic impact of future scenarios

According to the results generated in Action B1, no change of the main viticultural operation are expected in the future for the Rüdesheim pilot site. In the field of plant protection, there are currently only protective agents available which have a practical meaning: They have to be applied before the condition for an infection occur. This leads to many applications of fungicides and high costs during the growing season (8-10 applications are quite common in German viticulture). Future progress in the field of the development of effective curative plant protection agents (which can be applied after an infection), weather forecasting, disease prognosis and also in the field of breeding resistant grapevine varieties could contribute to a reduction of applications of pesticides in the future on the long term.

Figure 22 shows that steep slopes and terraces vineyards are under high economic pressure because of the high production costs. In many of those regions is viticulture forming the cultural landscape and is the main socio-economic factor with enormous co-meanings for the local tourism industry and local recreation. This vineyards have a climatic advantage due to the exposition to south, which became smaller in the recent years due the warmer temperatures. Also the available water capacity is very heterogeneous in steep slope regions and an increase of drought stress could be observed on some plots because of an increase of reference evapotranspiration and years with low rainfall, which led to a reduction of yield and quality for those plots. This development is projected to increase in the future (Hofmann and Schultz, 2016) and some growers already established cost intensive irrigation systems. Therefore, climate change led to an increase of the economic pressure for steep slope viticulture. On the other side, technical developments like the already mentioned crawler systems have reduced the drawback of difficult cultivation. Currently, prototypes of harvesters for steep slopes are intensively tested. Also drone systems for the application of fungicides are in development, which can distinctly reduce the effort for plant protection for steep slope and terraced vineyards in future.

Conclusions for Part 4

The levels of greenhouse (GHG) emissions, environmental indicators and socio-economic conditions were evaluated in order to assess the sustainability of current and future viticultural practices.

The current GHG emission were in the range of 1500 to 2100 kg eq CO_2/ha/year and can be considered as typical for most of the region. On plots, where harvest is performed mechanically, additionally 100-300 kg eq CO_2/ha/year, can be estimated. Pest and disease management and soil management were the most emitting interventions. About 30 % of the total emissions where indirect emissions.

The SEVE model produced no significant changes of management practices under future climate conditions. This is expectable, because rainfall projection show a high bandwidth for the region and therefore infection conditions will probably not change to a strong extent. If no new plant protection agents were available in future (especially with curative features), current fungicide application strategies will likely be applied also in future.

Beside of the GHG emissions, the most important environmental issues of viticulture in the Rheingau were the pollution of groundwater with nitrate, phosphate inputs to the surface water bodies caused by surface runoff and soil erosion, and the biodiversity. All of this issues are probably intensified by climate change. Higher temperatures increase the mineralization rates of nitrate, more rainfall in winter will increase the risk for nitrate leaching, higher rainfall intensity will increase surface runoff, and the strong change of environmental conditions will change the ecosystems and the abundance of species. Current programs by the Hessian agency for the environment in the frame of the water framework directive and the fertilizer ordinance consult the growers in order to protect the environment and biodiversity programs by the Federal Agency for Nature Conservation (BfN) help to protect natural habitats.

The socio-economic assessments showed strong differences, depending on the landscape characteristics, between the cultivation types terraces, steep slope and flat vineyards, ranging from roughly 19.000 Euro/ha (terraces) to 7.000 Euro/ha for flat vineyards. Under former, more unfavourable climate conditions, terraces and steep slopes could benefit more from their improved microclimate. But currently, where the climate conditions where more favourable for most of the region in most of the years, this advantage diminished occasionally. Also the globalized wine market, has increased the pressure to keep the costs under control. Many efforts were currently made to improve the mechanization and marketing strategies, in order to maintain steep slope viticulture, because this type of cultivation form the natural landscape and biodiversity hotspots, with many co-meanings for the local tourism, economy and local recreation.

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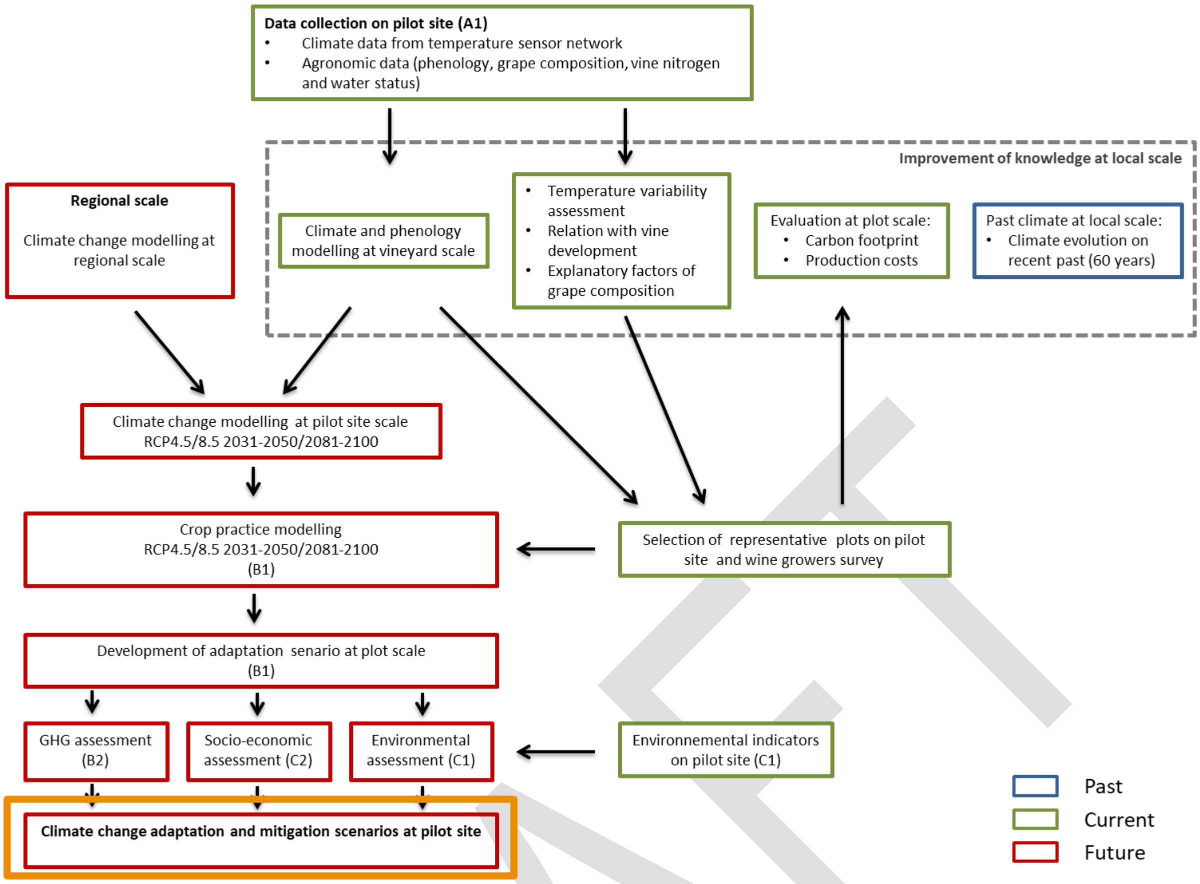
PART 5: CONCLUSION



The overall results obtained on the Geisenheim pilot site during the LIFE-ADVICLIM Project are represented on the following graphics.

Past climate / regional scale

1951-1980 / 1981-2010

Tmean growing season : **+ 0,7°C**

Huglin Index : **+ 157 degree-days**

Current / pilot site scale

Climate

High temperature variability :

- Daily amplitude : **1.3°C** for minimum T°C; **2.6°C** for maximum T°C
- Variability of Huglin index : **381 degree-days**

Strong effect of landscape features on temperature distribution

- Tn : with **elevation, cold spots in the landscape**
- Tx : with **elevation, hot spots in the landscape**
- Canopy WI : with **elevation**

Vine development

High intra-annual variability of phenology and maturity

Budbreak	Flowering	Veraison
 **10 days**	 **10 days**	 **15 days**

Must weight varied on same day (°Bx): 7 °Bx 

Grape variety : Riesling

Current / plot scale

GHG emissions

Average

1850 kg eq CO_2/ha/year

Variation

1500 to 2100 kg eq CO_2/ha/year

Most emitted practices during one campaign :

Pest and disease management; Soil maintenance

Major factors of variation

Engine power; Frequency of interventions

Socio-economic indicators

Cost average

13 214 €

Variation

6 793 € to 19 145 €

Most expensive practices during one campaign

Grape Harvesting; Pruning

Major factors of variation

Slope and terraces; Material; Number of workers

Environmental indicators

Water quality

Poor chemical status (Nitrates and pesticides)
(Ground water bodies)

Climate change

Higher temperature and earlier plant development)

Decrease of yield

Biodiversity :

Upper Middle Rhine Valley
(UNESCO World Heritage)

Future perspectives at pilot site scale

	2031 - 2050		2081 - 2100	
RCP 4.5	Huglin Index: + 120 degree.days	Flowering - 4 days; Veraison : - 7 days; Grape variety : No impact on grape variety	Huglin Index: + 270 degree.days	Flowering - 7 days; Veraison : - 12 days; Grape variety : No impact on grape variety
RCP 8.5	Huglin Index: + 120 degree.days	Flowering - 6 days; Veraison : - 8 days; Grape variety : No impact on grape variety	Huglin Index: + 570 degree.days	Flowering - 15 days; Veraison : - 23 days; Grape variety : Potential changes

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List of figures

List of tables

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