When climate change hits the vines:

A qualitative research on climate adaptation on viticultural practices in Rheingau

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LUCSUS
Lund University Centre for Sustainability Studies

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Abstract

Climate change impacts German viticulture through variations in temperature and precipitation patterns. Winegrowing being one of the main socio-economic sectors in Rheingau, implementing adaptation measures is vital to maintain this agricultural practice even in the future. The main focus of this study lies in exploring underlying factors that influence the implementation of climate adaptation measures, namely adaptation constraints, and opportunities. Adaptation constraints hinder the implementation of adaptation measures, whereas opportunities are enabling factors. Through semi-structured interviews, winegrowers' adaptive behaviour was investigated as they are the primary actors performing adaptation. Results show that the high costs of adaptation measures, governmental regulations, and consumers' demand for traditional German wines hinder the adaptation. Learning-by-doing and gathering knowledge about adaptation strategies encourage winegrowers to implement climate adaptation measures. Since climate adaptation is place- and context-specific, more research on vineyard level is needed to fully understand the viticultural adaptive capacity to climate change.

Key words: climate change, viticulture, adaptation measures, constraints, opportunities, Rheingau

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1 Introduction

"The world is definitely crazy and we have to deal with it" (Rheingau winegrower, 2022)

Viticulture, the cultivation of grapevines for winemaking, is a sensitive agricultural sector to climate change (Talanow et al., 2021; Buzási, 2021). Every grapevine variety has a narrow optimal climate range, leading to grapevines facing greater climate risk in both the short- and long-term compared to other crops (Mozell & Thach, 2014; Neethling et al., 2017). Thousands of different grapevine varieties originate from one species, *Vitis vinifera* L., and all cultivars have their evident genotype through berry composition, phenological features, and resistance to various environmental stresses (Wolkovich et al., 2017). Air temperature, precipitation, and solar radiation are the most influential atmospheric factors impacting grapevine development (Fraga, 2020), which all will face alterations due to climate change (Jobin Poirier et al., 2021). Therefore, winegrowing and its suitability for different regions, together with the productivity and quality of the grapes, are influenced by climatic conditions (Neethling et al., 2019; Jones & Webb, 2010; Lereboullet et al., 2013).

To cope with various impacts of climate change in socio-ecological systems, mitigation and adaptation are identified as key responding mechanisms (Neethling et al., 2017). While mitigation focuses on reducing greenhouse gas emissions, adaptation underscores the importance of adapting climate-sensitive sectors to already changed climatic conditions. Regarding the scope of this paper, the focus lies particularly on adaptation measures in grapevine farming.

Considering the perennial nature of grapevines, long-term and short-term adaptation measures on different spatial scales, based on context-specific factors, must be implemented (Neethling et al., 2017; Jobin Poirier et al., 2021). In this regard, every wine region has its unique contextual factors and understanding and knowledge of how place-specific features are interlinked with the regional climatic conditions. This further guides the choice of optimal adaptation measures on different temporal and spatial scales (Neethling et al., 2016). Adaptation to climate change can be autonomous or planned. Planned refers to policy-based responses, whereas autonomous adaptation is linked to farm-level adaptation, where winegrowers are the most influential decision-makers (Jobin Poirier et al., 2021). Despite planned and autonomous adaptation being equally important, adaptation is approached from the latter perspective in this study.

Climate adaptation is relatively new and precarious in viticulture (Neethling et al., 2017). Winegrowers' decision-making about climate adaptation is an ongoing process. The implementation of adaptation measures is influenced by the winegrower's psychological characteristics and social, economic, political, and biophysical factors in the surrounding environment (Garini et al., 2017; Mosedale et al., 2016).

This study aims first to understand climate change impacts in the Rheingau wine region. Second, how do winegrowers perceive vulnerability and risks connected to climate change? Third, I intend to investigate the underlying factors that either hamper or enable adaptation to climate change, also known as adaptation constraints and opportunities (Klein et al., 2014), at the level of individual winegrowers. Winegrowers' perspectives and perceptions are fundamental since they are the primary adaptation actors in the field. Finally, this thesis reflects on the adaptive capacity of the studied vineyards in Rheingau by synthesising answers from research questions 1, 2, and 3 in the discussion. This thesis builds on the following research questions:

1. What are the main climate change impacts on viticulture in Rheingau?
2. How are vulnerability and risks related to climate change perceived by winegrowers in Rheingau?
3. How do adaptation constraints and opportunities experienced by winegrowers influence the implementation of adaptation measures?

1.1 Relevance to sustainability science

Grapevine counts as one of the most important crops in Europe, having a key socio-economic and environmental role (Droulia & Charalampopoulos, 2021; Santos et al., 2020; Fraga et al., 2016). In western Germany, including the historical Rheingau wine region, viticulture serves as one of the main socio-economic sectors in society (Hofmann et al., 2021). Therefore, sustaining viticultural practices even under future climatic conditions with the help of adaptation processes is vital (Neethling et al., 2016).

Naulleau et al. (2021) acknowledge that proposed and published adaptation measures give guidance to decision-makers but, on the other hand, usually lack understanding of local adaptive capacity and ignore the main limitations of different adaptation measures. A majority of previous research has focused on adaptation constraints and opportunities through public institutions and community-based case studies (Klein et al., 2014). Consequently, top-down approaches provide potential solutions instead of actual and applicable ones (Neethling et al., 2017). Battaglini et al. (2009) highlight the importance of transferring scientific knowledge into practice to achieve effective and sustainable climate adaptation. Therefore, Merloni et al. (2018) stress how adaptation must be conceptualised as a place-specific phenomenon that requires more local-level research in order to understand the fundamental processes that influence the winegrowers' adaptive behaviour. Sacchelli et al. (2017) further highlight the need to validate winegrowers' perceptions of adaptation measures. Previous studies have revealed that winemakers' adaptive capacity is greater than winegrowers' due to several options to reduce climate change impacts in the final product, wine (Pickering et al., 2015). Therefore, this study focuses explicitly on winegrowers' adaptive capacity, thus, attempting to fill this research gap for Rheingau.

2 Background

This section introduces the idea of terroir, which is a crucial concept in viticulture. It also presents the characteristics of the Rheingau wine region and further outlines the main changes in climatic conditions. Thereafter adaptation measures in both short-term and long-term are described.

2.1 The concept of terroir

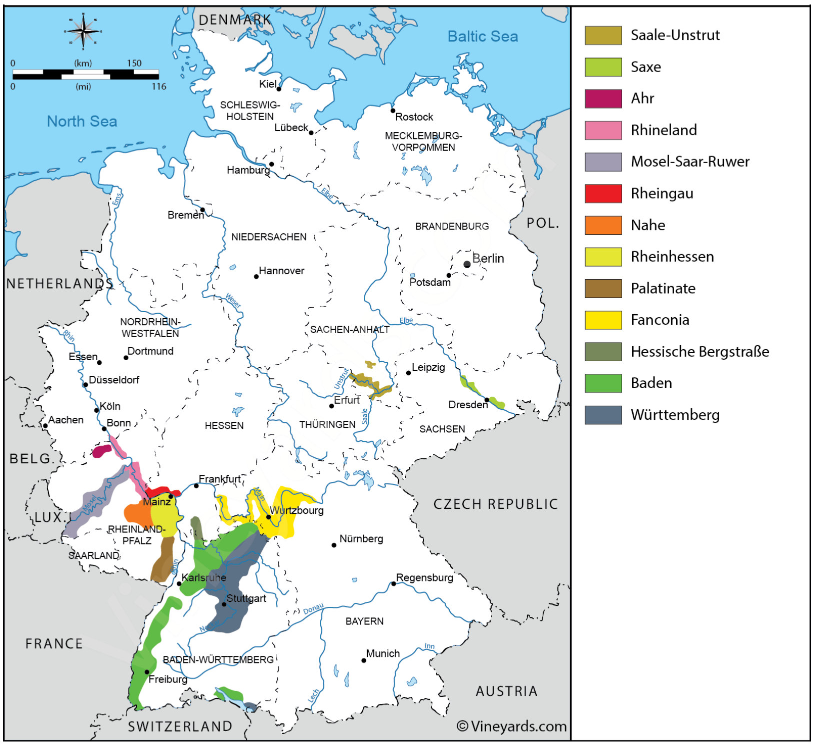
The climatic conditions determine the typicity and attributes of a wine as it controls the canopy microclimate, vine growth, vine physiology, yield, and berry composition (Santos et al., 2020). Each wine region has its unique characteristics regarding particular natural environments in the form of soil conditions, biodiversity, topography, and climatic conditions. In addition, human intervention through decisions on grapevine cultivars and different viticultural practices further influence the typicity of a certain wine. Terroir is a widely used concept that refers to a specific area where interaction between the physical and biological environment and applied viticultural practices create evident and distinctive characteristics for the wine (Santos et al., 2020). Various processes linked to terroir affect vine development and berry composition, making this concept central when determining wine quality and typicity (Fraga et al., 2012). Due to climate change, changes in the natural environment influence the typicity and style of German quality wines such as Riesling (Tissot et al., 2020; Stock et al., 2005).

2.2 Characteristics of Rheingau

Rheingau is a cool climate and steep slope wine region located in the federal state of Hesse (Hofmann et al., 2021). The location of Rheingau is displayed in Figure 1. The total grapevine cultivated area of 3191 hectares is located between Rüdesheim and Wiesbaden from west to east, respectively, and meets the Rhine river in the south and Taunus mountain in the north. The landscape is a rolling hillside towards the mountain, whereas the topography flattens towards the Rhine (Tissot et al., 2020). Despite being situated at 50° northern latitude, Rheingau has favourable viticultural conditions (Quénol et al., 2014). Riesling is the dominating grapevine variety occupying 78% of the cultivated area. Other grown varieties are Pinot Noir (12 %), Pinot Blanc (1.6 %) and Müller-Thurgau (1 %) (Tissot et al., 2020).

Figure 1

German wine regions



Note. A map illustrating German wine regions. Rheingau is shown in bright red, next to Rheinhessen, Nahe and Rhineland. Rheingau is located in western Germany. From: Vineyards.com, n.d. (https://vineyards.com/wine-map/germany). Copyright 2022 Vineyards Media LLC.

2.3 Changes in climatic conditions and grapevine phenology

Atmospheric conditions influence the phenological stages of the grapevine on two different time scales. Long-term climatic conditions determine the suitability of a given region for winegrowing by impacting the bioclimatic features of a specific location (Santos et al., 2020). Macroclimates define the range of thriving grapevine varieties in geographical areas, whereas meso- and microclimates impact terroir characteristics (Neethling et al., 2019). Furthermore, short-term weather variations through temperature, solar radiation, and water availability affect the annual yield, berry composition, and biomass production of vines (Santos et al., 2020).

According to Droulia and Charalampopoulos (2021), Europe will face an average temperature rise between 2.5 and 5.5 ◦C by the end of this century. Climate change creates changes in precipitation, its annual distribution, and evapotranspiration (Schultz, 2019). Viticultural suitability under future climatic conditions is predicted to decrease globally. However, grapevine growing is expected to become suitable in new areas, spreading to higher altitudes and latitudes (Naulleau et al., 2021).

Grapevine phenology describes the timing of different growth stages, all of them being climate-sensitive processes (Wolkovich et al., 2017; Sabir et al., 2018). The main phenological stages are budbreak, flowering, veraison, and maturation (Santos et al., 2020). Due to climate change, these stages are projected to face significant advancements, and additionally, the phenophase lengths between every stage will change (Fraga et al., 2016; Mosedale et al., 2016; Leolini et al., 2018). Therefore, viticultural planning and decision-making are closely related to characteristics of certain grapevine phenology (Neethling et al., 2016).

2.4 Climate adaptation measures in viticulture

Adaptation measures can be roughly divided into short-term and long-term measures (Santos et al., 2020). The vineyard-scale characteristics, for instance, soil type, grapevine variety, rootstock, and topography, influence adaptation strategies on different temporal and spatial scales (Neethling et al., 2017). Therefore, this categorisation is not restrictive but should be seen as a guide for understanding the different types of adaptation measures. For instance, irrigation can be seen as a long-term adaptation measure due to its high costs and challenges in implementation (Tissot et al., 2020). Still, on the other hand, Santos et al. (2020) categorise irrigation as a short-term measure since it can, within a season, increase the yield and improve its quality.

2.4.1 Short-term adaptation measures

Short-term adaptation measures (see Table 1) generally focus on particular challenges and threats and are seen as the primary protection strategy to cope with climate change impacts (Talanow et al., 2021). Short-term vineyard interventions usually occur during the grapevine growing season and mainly focus on management practices (Santos et al., 2020). Therefore, according to Nicholas and Durham (2012), short-term adaptation regularly requires innovation, monitoring, and quick decision-making from winegrowers.

Table 1

Overview of short-term adaptation measures in viticulture

Adaptation measure	Aim of adaptation measure	References
Cover crops	Reduce soil evaporation, reduce soil erosion, improve water holding capacity of soils	Naulleau et al., (2021); Santos et al., (2020); Neethling et al., (2017); Fraga et al., (2012); Tissot et al., (2020)
Mulching	Reduce thermal and water stress, limit soil evaporation, reduce soil erosion	Gutiérrez-Gamboa et al., (2021); Fraga & Santos (2018); Naulleau et al., (2021)
Canopy management	Control the sunlight exposure on leaves and grapes, create optimal airflow within the vine canopy	Neethling et al., (2017); Jobin Poirier et al., (2021); Naulleau et al., (2021)
Delaying winter pruning	Delay the on-set of budbreak in the spring	Mosedale et al., (2016); Sabir et al., (2018); Neethling et al., (2016); Gutiérrez-Gamboa et al., (2021)
Use of heaters & wind machines	Reduce frost damage on buds	Neethling et al., (2017); Nicholas & Durham, (2012)

Note. This table shows an overview of short-term adaptation measures used in viticulture. The common practices are listed and their main aim is described. Author's own creation.

2.4.2 Long-term adaptation measures

Long-term adaptation measures (see Table 2) are implemented to strengthen vineyards' adaptation to climate change during several seasons, and long-term adaptation measures take place even before planting the vineyard (Santos et al., 2020). Considering that the commercial lifespan of vines ranges from 20 years up to 50-60 years (Droulia & Charalampopoulos, 2021; Babin et al., 2021), long-term adaptation is highly vital to maintain the sustainable productivity of the vines (Lereboullet et al., 2013; Neethling et al., 2019). Long-term adaptation measures include transformation and structural changes on the vineyard (Talanow et al., 2021). Compared to short-term adaptation measures, long-term actions usually require more investment, and therefore winegrowers typically prefer short-term measures (Santos et al., 2021). The amount of experience in viticultural practices influences the capacity to implement long-term adaptation measures. Winegrowers with greater experience are more prone to reflect on long-term changes due to experienced challenges and risks in the past (Nicholas & Durham, 2012).

Table 2

Overview of long-term adaptation measures in viticulture

Adaptation measure	Aim of adaptation measure	References
Choice of rootstock, grapevine variety & clones	Reduce risks for yield losses, utilise specific characteristics of cultivars (such as late-ripening and drought resistance while maintaining the typicity of wine	van Leeuwen et al., (2019); Fraga (2020); Santos et al., (2021); Santos et al., (2020)
Row orientation, planting density and trunk height	Restrict solar radiation interception on vines, improve water holding capacity of the soils, reduce soil erosion, regulate an optimal temperature for the bunch zone of vines	Santos et al., (2021); Babin et al., (2021); Mozell & Thach, (2014); Gutiérrez-Gamboa et al., (2020); Naulleau et al., (2021); Neethling et al., (2019); van Leeuwen et al., (2019)
Site selection	Find most suitable sites for winegrowing, spreading viticultural practices to higher latitudes and altitudes	Gutiérrez-Gamboa et al., (2020); Leolini et al., (2018); Fraga et al., (2016); Fraga (2020); Santos et al. (2020)
Irrigation	Secure enough water resources for the vines	Hofmann et al. (2021); Tissot et al., (2020); Fraga (2020)

Note. This table shows an overview of long-term adaptation measures used in viticulture. The common practices are listed and their main aim is described. Author's own creation.

3 Theory

This section is structured in three main parts, all of them building on each other. First, the key concepts of climate adaptation in general are introduced. After that, the IPCC's synthesis of factors influencing the implementation of adaptation measures, namely adaptation constraints, and opportunities, is presented. Finally, the conceptual framework of winegrowers' decision-making regarding adaptation is explored.

3.1 Vulnerability

According to Lereboullet et al. (2013) and Nicholas and Durham (2012) vulnerability can be explained as to what extent a system is affected after experiencing exposure to change or threat, including the aspect of sensitivity. Vulnerability to climate change can be defined as a tendency to be adversely affected by climate-related events and sensitivity to damage or loss (Jones et al., 2014).

Decision-making considering the adoption of particular adaptation measures is influenced by individuals' perception of vulnerability to climate change (Mosedale et al., 2016). Furthermore, vulnerability to climate change can be decreased by building up the adaptive capacity of climate-sensitive activities, such as viticultural practices (Jones & Webb, 2010). Neethling et al. (2017) acknowledge that to improve the adaptive planning in the viticultural sector, contextual vulnerability must gain more understanding. This refers to local vulnerability in individual vineyards and encourages deeper knowledge on a local scale.

3.2 Adaptive capacity

Adaptive capacity is a system's ability to adapt to and recover from changes in local conditions and further reduce negative impacts from changes by implementing reactive and anticipating adaptation measures in both short-term and long-term, respectively (Merloni et al., 2018). Lereboullet et al. (2013) further address how the vulnerability is a function of adaptive capacity. Adaptive capacity is further influenced by constraints, opportunities, and limits that impact the actors' ability to implement various adaptation measures to cope with climate change (Klein et al., 2014).

To strengthen the adaptive capacity of socio-ecological systems such as viticultural practices, both biophysical and human factors play a crucial role (Lereboullet et al., 2013). Every wine region has its distinct characteristics when it comes to local climates, terrain complexity, and biophysical mechanisms, such as phenological cycle (Neethling et al., 2019; Mosedale et al., 2016), which together with regional socio-economic and cultural conditions impact the local adaptation processes and the overall adaptive capacity (Reidsma et al., 2010). In addition, winegrowers' adaptive decision-making on the farm level is influenced by specific adaptation constraints and opportunities of grapegrowing sites, together with farmers' personal experience with climate adaptation measures (Merloni et al., 2018).

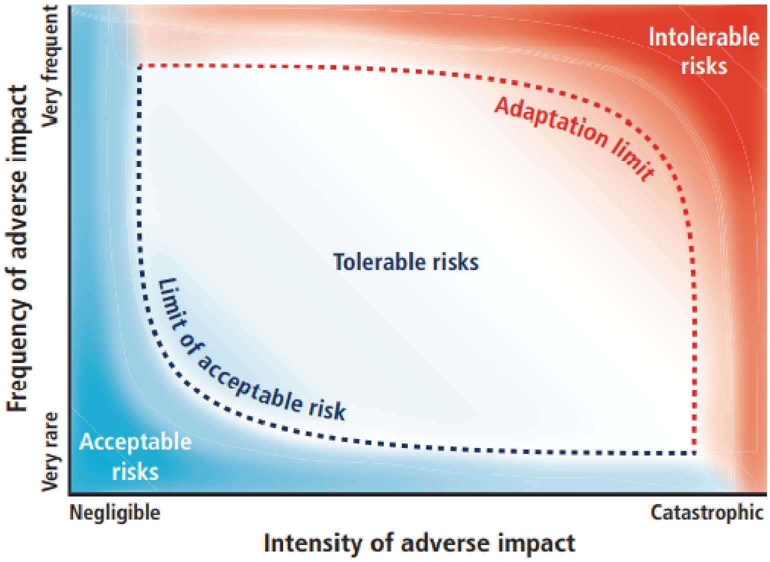
3.3 Risk

Winegrowing faces various risks due to short- and long-term climate variability (Jones & Webb, 2010). Risk is a fundamental part of understanding climate adaptation, and risks can be divided into acceptable, tolerable, and intolerable risks. Acceptable risks are defined as risks that do not require efforts in risk reduction through climate adaptation measures. Tolerable risks require the use of adaptation measures to keep risks within reasonable levels (Klein et al., 2014). Intolerable risks, in turn, are threats that lack a practicable or affordable adaptation measure and consequently become unavoidable risks (Moser & Ekstrom, 2010). Adaptation limit illustrates the point where intolerable risk has to be accepted by the actors (see Figure 2). Two types of adaptation limits exist, namely soft and hard limits. For soft limits, current adaptive action is not available, but possible adaptation options and measures may become accessible in the future, and therefore the adaptation limit can be flexible. This can be due to changing values and attitudes or innovation and resources becoming more obtainable. Hard limits are characterised with no adaptation options even when expanding the future planning window for adaptation measures, and therefore hard limits are time-insensitive (Klein et al., 2014).

The categorisation of risks varies on different temporal and spatial scales. Decision-making concerning adaptation measures is influenced by actors' individual perceptions of whether a risk is recognised as acceptable, tolerable, or intolerable (Klein et al., 2014). According to Lereboullet et al. (2013), the perception of changes in climatic conditions is vital to recognise among winegrowers since it influences especially the implementation of long-term adaptation measures. Talanow et al. (2021) acknowledge that previously experienced climatic stresses, together with perceived risks regarding adaptive capacity, impact winegrowers' adaptive behaviour.

Figure 2

A conceptual model of acceptable, tolerable and intolerable risks



Note. Conceptual model illustrating the division between acceptable, tolerable and intolerable risks to climate change. Frequency and intensity of climate-related risks can vary, consequently impacting the actors' view of risk tolerance, which is visualised with dotted lines. From "Adaptation Opportunities, Constraints, and Limits" by Klein et al. (2014), In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Copyright 2022 Intergovernmental Panel on Climate Change (IPCC). Reproduced with permission.

3.4 Adaptation constraints and opportunities

Climate adaptation and the overall adaptive capacity of a system are influenced by adaptation constraints and opportunities (Klein et al., 2014; Mosedale et al., 2016). Neethling et al. (2019) underscore how adaptation constraints and opportunities in viticulture are influenced by the complex interaction between biophysical and numerous human factors on various temporal and spatial scales. Although adaptation constraints and opportunities are often viewed distinctively they are complementary features since they both influence the overall adaptive capacity of a system where actors take advantage of opportunities and, at the same time, are restricted due to constraints (Klein et al., 2014). Followingly, adaptation constraints and opportunities are defined.

Adaptation constraints are components that make the planning and implementation of adaptation measures more difficult (Klein et al., 2014). The variety and effectiveness of adaptation actions are restricted due to adaptation constraints, and therefore actors experience obstacles in retaining their practices. In contrast, adaptation opportunities ease the planning and implementation of adaptation measures by increasing the range of adaptation options or providing supplementary benefits.

Opportunities improve the actors' ability to maintain and secure their existing objectives and intentions, such as viticultural practices (Klein et al., 2014). The availability of adaptation opportunities and options influences the overall adaptive capacity (Jones & Webb, 2010).

3.4.1 Adaptation constraints

Biophysical constraints

Human and natural systems' capacity to adapt to climate change is connected to the surrounding physical environment, where climate itself creates impact. Access to water and soil conditions are examples of physical constraints (Klein et al., 2014). Therefore, vineyard characteristics can pose physical constraints to different adaptation measures (Neethling et al., 2019; Mosedale et al., 2016).

Biological constraints are genetic, physiological, and behavioural factors linked to individuals' and populations' tolerance to climate change. The phenological cycle and genetic variation are some of the main features influencing organisms' adaptive capacity. In addition, pests and diseases can cause ecosystem constraints (Klein et al., 2014).

Economic constraints

Economic constraints relate to fluctuations in macroeconomic conditions and how for instance, national or global financial crises can hamper climate adaptation. The agricultural sector is one of the most vulnerable sectors to economic constraints (Klein et al., 2014). Additionally, adaptive decision-making in viticulture is hampered by global market regulations since only a small number of grapevine varieties dominate the market as an economic constraint (Mosedale et al., 2016). Under climate change, the adoption of other, less popular cultivars could increase the adaptive capacity of vineyards, but due to the oversupplied market in the wine world, cultivating new varieties and consequently new wine characteristics create difficulties in finding profitable markets (Babin et al., 2021).

Financial constraints

Financial capital plays a significant role in implementing adaptation measures since it enables or hinders the adoption of different strategies through credit, insurance, and earnings on the individual household level (Klein et al., 2014). Personal financial challenges can hinder a single vineyard's capacity to adapt as motivation to adapt is reduced due to financial costs (Orberghaus et al., 2010; Pickering et al., 2015; Bagagnan et al., 2019). Additionally, high costs for insurance can become a constraint to implementation (Klein et al., 2014).

Human resource constraints

Knowledge deficits often hamper decision-making regarding adaptation measures. Uncertainty about future changes in climatic conditions is connected to increased demand for information (Klein et al., 2014). In addition, plenty of adaptation measures are precautionary or proactive in character, which means that planning and implementation of measures will need to happen before climate events. Therefore, available information plays a critical role. Uncertainties and lack of information complicate especially autonomous adaptation of winegrowers (Osberghaus et al. 2010).

Social and cultural constraints

Worldviews, cultural norms, and societal values can create constraints for climate adaptation as the perception of risk, prioritisation of different adaptation measures, and understanding of vulnerability are all influenced by social and cultural factors (Klein et al., 2014; Osberghaus et al., 2010). Sense and attachment to particular places is an example of how cultural and societal attachment influence the adoption of adaptation measures and can create a barrier to action (Mosedale et al., 2016).

Governance and institutional constraints

Societal institutions and their decision-making regarding the implementation of particular adaptation measures can pose constraints to overall climate adaptation, especially if they fail to support a specific group of actors in a particular context (Klein et al., 2014). Institutional adaptation can create constraints through complex governance networks where numerous actors and agencies have varying perceptions of climate change and different understanding of adaptation opportunities and constraints (Raymond & Spoehr, 2013).

Constraints and competing values

Conflicting values and preferences can create constraints to adaptation, and therefore some adaptation actions can be experienced as maladaptive, reinforcing vulnerability (Klein et al., 2014). For instance, implementing irrigation systems in response to warmer and drier climates may negatively impact the biodiversity of vineyards where native components can disappear due to changes in the vineyard environment (Buzási, 2021). Therefore, it is crucial to evaluate and ensure the applicability and sustainability of each climate adaptation measure in viticulture before implementation to reduce the risks of maladaptive consequences.

3.4.2 Adaptation opportunities

Awareness raising

According to Raymond and Spoehr (2013), Australian winegrowers who accepted human-induced climate change were more likely to implement adaptation measures such as cover crops to improve the soil structure and water holding capacity than respondents who denied human-induced climate change. This is related to positive stakeholder engagement in IPCC's categorisation of climate adaptation opportunities (Klein et al., 2014). Additionally, policymaking plays a critical role in creating an environment where winegrowers can implement adaptation measures (Reidsma et al., 2010).

Capacity building

Bowen et al. (2012) acknowledge that the development of human capital is one crucial part of dealing with climate shocks and improving resilience. Authors highlight that with better education and information about climate change, people and particularly farmers, can understand climatic conditions and find coping strategies connected to management decision-making. The development of social capital is also part of capacity building and, therefore, an opportunity for climate adaptation (Klein et al., 2014). Pickering et al. (2015) address that social capital appears in social connections, networks, and collective action, where winegrowers can support each other by lending machines and sharing staff and expertise. This connects further to research, data, education, and training, where knowledge is shared via different networks (Klein et al., 2014).

Learning

Neethling et al. (2017) describe how winegrowers enhanced the adaptive capacity of vineyards through learning experiences and shared knowledge. Learning-by-doing as a method to guide adaptation processes in viticulture is highlighted by Nicholas and Durham (2012). The authors found that winegrowers' learning from trial and error experiences in management practices had the strongest influence on winegrowers' decision-making.

Nicholas and Durham (2012) also address that shared knowledge and information between winegrowers and other viticultural actors guides decision-making at the farm level. This is relevant for experience with climate vulnerability (Klein et al., 2014) since shared knowledge and experience among winegrowers can increase the adaptive capacity of vineyards while decreasing their vulnerability.

Innovation

Climate adaptation can be enhanced through technological change (Klein et al., 2014). Furthermore, Chhetri et al. (2012) acknowledge how technological innovations in the agricultural sector should consider farmers' knowledge. Only then can place-specific adaptation measures connected to technological advancements be effectively applied.

3.5 The conceptual framework of winegrowers' decision-making process

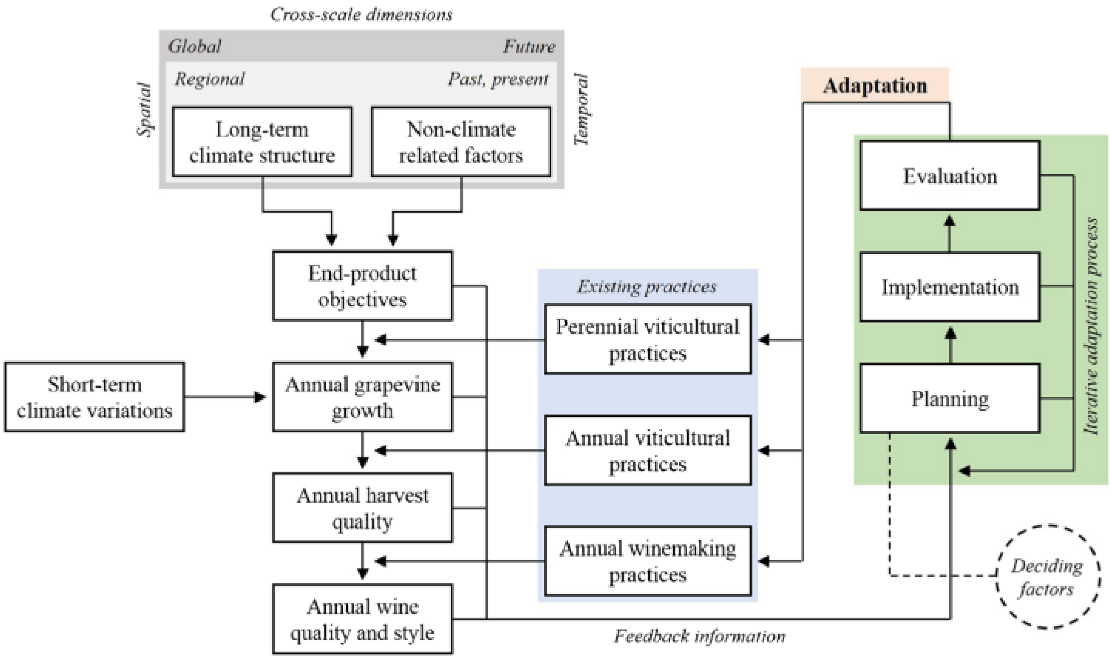
Understanding the system's vulnerability to climate change is an essential part of planning adaptation measures. Reidsma et al. (2010) argue that adaptation frameworks should, in the first place, focus on stakeholders', such as winegrowers' perspectives, instead of modelling as a top-down approach. Reidsma et al. (2010) further identify three steps in assessing the effectiveness and feasibility of adaptation measures, which are the following:

1. Evaluate current vulnerability to changes in climatic conditions
2. Assess climate risks
3. Create adaptation strategies on the vineyard level and further policy level.

The steps named above can be integrated into the conceptual framework by Neethling et al. (2017) that captures winegrowers' multifaceted and dynamic decision-making process concerning climate change adaptation. According to Talanow et al. (2021), effective adaptation to climate change can be achieved by understanding winegrowers' perceptions and responses to climate change since they are the primary land users and key decision-makers. Steps 1 and 2 (Reidsma et al., 2010) are connected to the "non-climate-related factors" and "long-term climate structure" in the conceptual framework's grey box (see Figure 3). Additionally, step 3 (Reidsma et al., 2010) describes the whole process of adaptation, illustrated in the green box. That includes planning, implementing, and evaluating different adaptation measures (Neethling et al., 2017).

Figure 3

The conceptual framework of winegrowers' decision-making process



Note. This figure shows a conceptual framework of winegrowers' decision-making process. Deciding factors related to different adaptation constraints and opportunities guide the autonomous decision-making of winegrowers regarding the implementation of adaptation measures. Adaptation can be directed to perennial and annual practices, while short-term and long-term factors influence the overall adaptation process. From "Assessing local climate vulnerability and winegrowers' adaptive processes in the context of climate change" by Neethling et al. (2017). *Mitig Adapt Strateg Glob Change 22*, p.780. Copyright 2022 Springer Nature B.V.

Furthermore, this framework illustrates how the end-product objectives, such as the style and typicity of the wine, have a direct connection to decision-making regarding perennial viticultural practices, for instance, choosing of grapevine variety, type of rootstock, and geographical location of a vineyard (Coulon-Leroy et al., 2012). Decisions related to perennial practices are often guided by the long-term, regional climatic conditions that, under climate change, pose new challenges to decision-making for winegrowers (Lereboullet et al., 2013). On the other hand, annual viticultural practices focus on seasonal climate variabilities through decision-making regarding soil and harvest management, among others (Neethling et al., 2017). Short-term, seasonal variations in climate, in terms of extreme rain, frost, or drought, directly influences vine growth and development, further impacting the annual harvest quality (Leolini et al., 2018). Annual variations often require reactive responses from winegrowers to maintain the fundamental vineyard functions. On the other hand, anticipatory responses focus on taking action before a critical threshold is reached and therefore are often categorised as long-term adaptation measures (Neethling et al., 2017).

4 Method

4.1 Research approach

This study examines winegrowers' perception of climate change and further implementation of various adaptation measures; a phenomenological research design is considered suitable (Creswell & Creswell, 2018). This type of qualitative research describes individuals' experiences of a particular phenomenon, climate change, and adaptation work, and interviews as a method of collecting data are typically used. The goal of using the phenomenological approach is the researcher's aim to understand the participants' experiences from their subjective points of view (Seidman, 2013). On the other hand, Seidman (2013) highlights that understanding another person perfectly is impossible, but coming as close as possible to understanding their experience is crucial for the phenomenological approach. According to Klein et al. (2014), perception of climate change and experienced climate-related risks influence the decision-making regarding adaptation measures. Therefore, a methodological approach that can facilitate understanding of how and why different factors impact climate adaptation from winegrowers' point of view is relevant for this study.

To my knowledge, this thesis is the first to apply IPCC's climate adaptation constraints and opportunities to viticultural research. Therefore the theoretical categorisation by Klein et al. (2014) is the primary analytical entry point for this study. Additionally, previous scientific research on adaptation measures in viticulture and empirical data from interviews contribute to deeper knowledge, specifically about climate adaptation work in Rheingau.

4.2 Literature review

A literature review was conducted to answer the first research question about climate change impacts on viticulture. Previous scientific research was used to explore various climate change impacts on the wine sector, focusing on the Rheingau wine region in Germany.

Several databases, such as LUBSearch, Scopus, and Google Scholar, were used to gather scientific literature for the literature review. The main keywords included in search terms were "climate change," "impact," "adaptation," "viticulture," "decision-making," "constraint," "barrier," "opportunity," "adaptation measure," "adaptation strategy" "Germany" and "Rheingau." Based on keywords, 65 articles were reviewed, and further, the most relevant 20 articles for research questions were included in the literature review. The publishing year of the chosen articles varies from 2005 to 2021.

4.3 Sample and sampling strategy

Since climate adaptation is place-specific (Neethling et al., 2017), this study's scope was narrowed to Rheingau. The aim of conducting a purposive sampling for interviews was to consciously define the appropriate group of participants who would contribute with valuable answers to research questions (Silverman, 2015; Bryman, 2016). Participants for the interviews explicitly represent winegrowers, excluding, for instance, winemakers. Another step in purposive sampling was to allow a researcher in viticulture from Rheingau to select the first sample of 10 contacted winegrowers. Due to a lack of answers from the first sampling, I reached out to additional 68 winegrowers listed on the webpage www.rheingau.de/weingueter and to 4 additional winegrowers through www.rheingau.com/enjoywines. Some of the interviewed winegrowers gave contacts to their colleagues in other vineyards, which resulted in more interviews.

4.4 Interviews

The interview guide (see Appendix 1) for this study was designed to align with the recommended standard structure presented by Creswell and Creswell (2018, p. 191). Furthermore, the interview included the three steps in assessing the effectiveness and feasibility of adaptation measures by Reidsma et al. (2010). The first part of the interview consisted of background questions about the vineyard and the winegrower. The second theme was about winegrowers' perceptions and experienced vulnerability and risks connected to climate change. The third theme included specific questions about climate adaptation measures and what constraints and opportunities influence the implementation, further concluding with the overall adaptive capacity of the vineyard.

According to Silverman (2015), semi-structured interviews are common in qualitative research, focusing on a relatively small number of respondents, using prepared but open-ended questions that guide the interview while allowing the respondent to elaborate answers relatively freely. Semi-structured interviews provide detailed information about complex problems while at the same time allowing the interviewer to explain and rephrase questions during the interview to avoid confusion and misunderstanding (Neethling et al., 2017).

All six interviews were conducted as an online meeting via Zoom due to the convenience regarding time and economic resources when interviewing participants in a geographically different area (Silverman, 2015). Additionally, Bryman (2016) highlights the major benefits of online interviews: the flexibility regarding the time of interviews and the fact that online interviews may encourage some participants to participate more than face-to-face interviews. In addition, the interview guide, including all the interview questions, was sent to all participants before the interview so that respondents could reflect on their answers in advance (Bryman, 2016). This, I believe, allowed winegrowers to feel more confident and comfortable with the actual interview, and the time allocated to the interview was effectively being used. Interview time ranged from half an hour to two hours.

4.5 Pilot study

Before the actual interviews, a pilot study with one Swedish winegrower was conducted to finalise the interview guide's structure and to minimise any confusion with the interview questions. In addition, the interview duration was checked, and further, the pilot study ensured that the goals of the overall research would be met through the interviews (Neethling et al., 2017).

4.6 Data analysis and operationalisation scheme

Interview transcripts were analysed using qualitative content analysis. According to Neethling et al. (2017), qualitative content analysis interprets the content of text data subjectively by classifying and identifying themes or patterns. Moreover, directed content analysis as one distinct approach to qualitative content analysis focuses on extending or validating a theoretical framework or theory (Hsieh & Shannon, 2005). This is in line with this thesis as the conceptual categorisation of adaptation constraints and opportunities by Klein et al. (2014) is used to identify research questions and interview questions. The data from interviews with winegrowers were analysed alongside the categorisation of constraints and opportunities performed by Klein et al. (2014), characteristic of directed content analysis (Hsieh & Shannon, 2005). A deductive method guided the establishment of suitable categories for this study since some of the original IPCC categories for adaptation constraints and opportunities were not applicable in this research (Creswell & Creswell, 2018).

4.7 Ethical considerations

Before conducting the interviews, all participants were informed about the project's goals and how interviews would be carried out through open-ended questions. Interviewees were notified that their participation is completely voluntary, that all answers are anonymous, and that they have the right to withdraw participation at any time, as suggested by Kvale (2009). Additionally, a consent to participate and to be recorded (see Appendix 2) was signed by all the participants before the interview. The recordings were carefully stored, the author of this thesis having only access to them.

4.8 Methodological limitations

Purposive sampling creates one of the main methodological limitations for this study as it can not contribute to the generalisation of a group or phenomenon (Bryman, 2016). This further restricts this study from developing an overall picture of Germany's viticultural climate adaptation responses but can be seen as an in-depth study of a small group of participants in the Rheingau wine region.

Due to the timeframe of this thesis, interviews were conducted during spring at the beginning of the growing season, which is a busy time for winegrowers. Some interviews were neglected or postponed due to time considerations. Conducting interviews in English became one of the biggest barriers for this study as relatively many German winegrowers did not feel comfortable or capable of answering interview questions in English.

Due to using Zoom as a platform for the interviews, no observations on site were able to be gathered. I believe that visiting vineyards would add more detailed information about different adaptation measures and underlying influencing factors as winegrowers would have the possibility to demonstrate specific conditions on the actual vineyard.

Besides the measures taken to limit ethical difficulties, it is important to acknowledge that researchers can never be fully unbiased with research methods or analysing the results. For instance, in line with Seidman (2013), my Nordic background can influence how the results are interpreted as my cultural and knowledgeable frame differs from the interviewed German viticultural experts.

5 Results and analysis

The analysis consists of three main sections, sequentially answering and analysing the three research questions. First, climate change impacts in Rheingau and future projections are investigated. Second, winegrowers' perception of climate change, vulnerability aspects, and risks related to climate change are presented. After that, climate adaptation processes from the winegrowers' perspective are explained through adaptation constraints and opportunities. The first part builds on data from the literature review and conducted interviews with winegrowers. The second and third parts focus on the empirical data from interviews. Hereafter, interviewed winegrowers are referenced as winegrower 1, W1. Below, Table 3 presents the main characters of interviewed winegrowers.

Table 3

The main characteristics of the interviewed winegrowers in Rheingau

Winegrower	Main varieties	Age of the vines	Area (hectares)	Type of practice
W1	Riesling, Pinot Noir, Pinot Gris, Pinot Blanc	Oldest 60 years, majority over 35 years	220	Conventional
W2	56% Riesling, 26% Pinot Noir, 7% Pinot Blanc	3 to 62 years	23	Conventional with some organic aspects
W3	80% Pinot Noir and 10% Riesling	Oldest 50 years, majority 30 years	9	Conventional
W4	Riesling	Oldest 37 years	81	Organic
W5	85% Riesling and 12% Pinot Noir	Oldest 70 years	38	Organic
W6	85% Riesling, 15% Pinot Noir	5 to 60 years	7,5	Organic, but changing to biodynamic

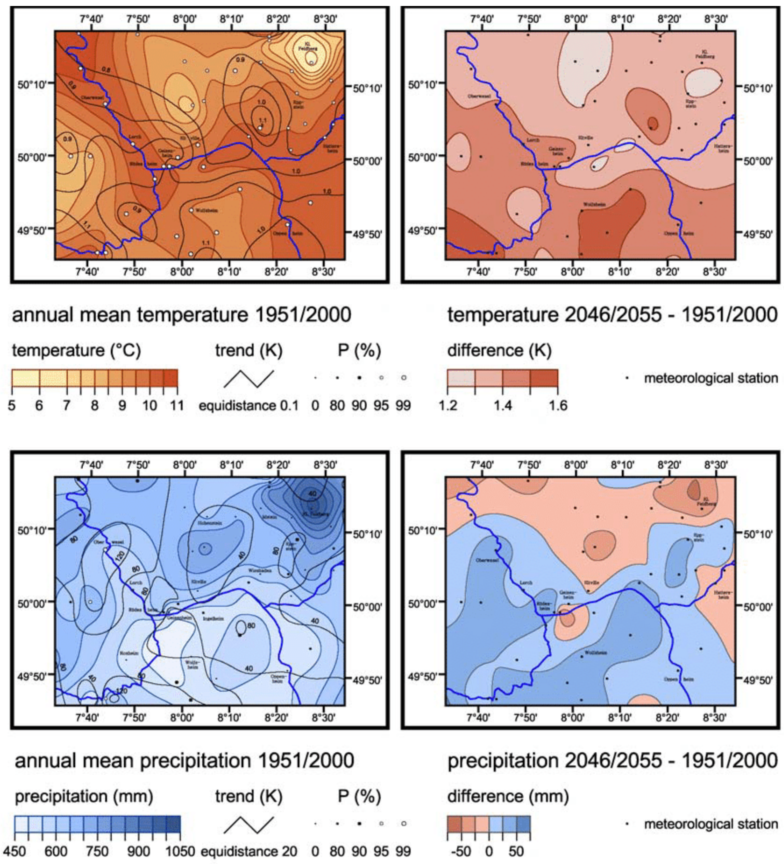
Note. This table shows the main attributes of the studied winegrowers and their vineyards in Rheingau. Riesling is the most common variety among winegrowers, only W2 grows more Pinot Noir than Riesling. The age of the vineyards is rather similar among all winegrowers but the growing area differs significantly. Half of winegrowers use conventional practices and the other half organic practices. Author's own creation.

5.1 Projections for temperature and precipitation

The climatic conditions in Rheingau are oceanic, and temperate, characterised by the mean annual temperature of 10.5 °C and mean annual precipitation of 544 mm (Tissot et al., 2020, Hofmann et al., 2021). When comparing changes in mean temperatures between the periods 1951-1980 and 1981-2010, the annual mean temperature has risen 0.7 °C in Rheingau (Tissot et al., 2020). The temperature increase is calculated to continue at a pace of 0.42 °C per decade and 2.04 °C overall between 2000 and 2049 in the key winegrowing regions (Gutiérrez-Gamboa et al., 2020). In addition to increasing temperatures, future projections show a decrease in precipitation in Rheingau as well (see Figure 4) (Stock et al., 2005).

Figure 4

Changes in temperature and precipitation in Rheingau



Note. Maps of Rheingau and Rhine valley show the annual mean temperature and precipitation and its distribution for the past years 1951 to 2000 and for the future 2046 to 2055. The future projections are expressed as the difference between the reference period and the future. From “Reliability of Climate Change Impact Assessments for Viticulture” by Stock et al. (2005). *Acta Hort, 689. Proc. VIIth IS on Grapevine.* Copyright 2022 International Society for Horticultural Science.

Five interviewed winegrowers had experienced warmer temperatures due to climate change. Additionally, all winegrowers mentioned changes in precipitation patterns. W4 stated: “climate change means you don’t get the rain that you need at the time when you need it.” Especially during summer, overall precipitation is lower, but more extreme rain is experienced (W2). Further, W1 mentioned that weather patterns don't change as regularly as in the past, which W6 also experienced: "The biggest problem is that the water is not coming permanently, it comes like a storm, like heavy rain, and then 2 or 3 months nothing". Overall, W2 concluded about climatic features of Rheingau: "It's not a cool climate region anymore like it was 60-70 years ago". Experienced impacts from climate change align with findings from scientific research explored above.

5.1.1 Changes due to temperature variation

In Rheingau, the grapevine budbreak occurs today 8-10 days earlier compared with the year 1950. Additionally, veraison, the start of the ripening process has advanced by 18-23 days in the same time frame (Wolkovich et al., 2017; Gutiérrez-Gamboa et al., 2021). Grapevine varieties, such as Riesling, were chosen due to their ripening window being between 10 September and 10 October (van Leeuwen et al., 2019). Both ripening and veraison will advance by approximately 12 days by 2050 in Rheingau (Stock et al., 2005). Consequently, the first day of harvest in Rheingau will advance a couple of weeks from 2000 to 2050, occurring in September instead of October (see Figure 5) (Stock et al., 2005).

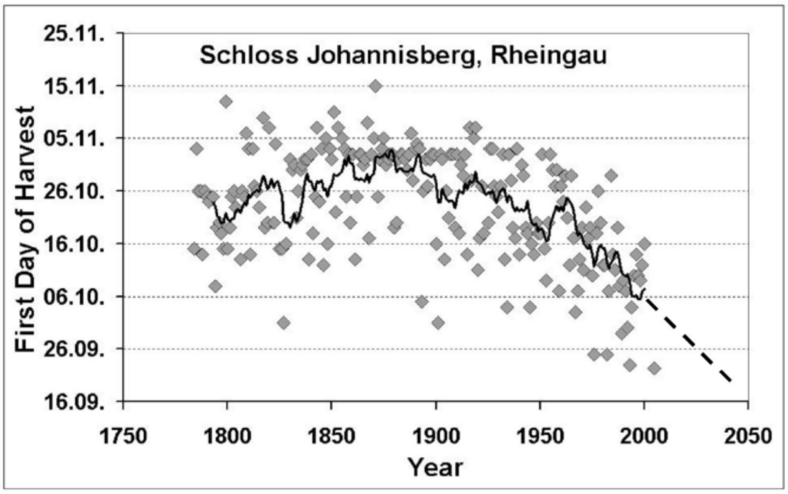
Regarding the interviews, the length of phenological stages, especially the harvest period, has gotten shorter and more compact, increasing workload intensity (W3, W4 & W5). W6 explained how the beginning of harvest has moved three weeks earlier in comparison to 40 years ago. This is in line with Stock et al. (2005).

The final composition of acids, sugar, aromas, and colour of the wine depends on temperature conditions during ripening (van Leeuwen et al., 2019; Sabir et al., 2018). Moderate temperatures provide the best conditions to create balanced wine, while increased temperature risks ripening to occur under higher temperatures (Santos et al., 2020; Mozell & Thach, 2014). This further leads to unbalanced fruit composition where the sugar content is excessive, and the level of acidity is low (Mosedale et al., 2016; Neethling et al., 2019). Consequently, the end-product lacks aromatic complexity and overall freshness, which influences the typicity of the wine (Fraga et al., 2016).

On that note, W4 explained that "Riesling is not a grape variety like Pinot Noir or Cabernet Sauvignon that is used to the hot climate." Therefore, "high temperatures during the harvest period change the aroma profile and the acidity and sugar level" (W2), which is consistent with Mosedale et al. (2016). Changes in wine typicity due to climate change influence the ideology of terroir in Rheingau, and traditional features of the wines can therefore be at risk. In the past, W2's grandfather and father had problems achieving enough ripeness before harvest, but today the problem is the opposite, as the risks are connected to overripening. Further, W6 explained how overripening due to increased temperatures can lower the total yield. In addition, increased sun exposure creates sunburns on grapes, which negatively affects the harvest quality (W1, W2 & W3).

Figure 5

Changes in the first date of harvest at Schloss Johannisberg, Rheingau



Note. Figure illustrates the first date of harvest at Schloss Johannisberg, Rheingau between 1784 and 2003. It is evident that the first date of harvest has advanced especially from the late 19th century. Estimated first date of harvest is presented until the year 2050. From "Reliability of Climate Change Impact Assessments for Viticulture" by Stock et al. (2005). *Acta Hort, 689. Proc. VIIth IS on Grapevine.* Copyright 2022 International Society for Horticultural Science.

5.1.2 Changes in water availability

According to Hofmann et al. (2021), prolonged periods without precipitation were detected in Germany between 2018 and 2020, at worst leading to a water deficit. Irrigation systems do not often exist, which increases the risks for quantity and quality losses of yields (Hofmann & Schultz, 2015). It is further acknowledged that southwest Germany, including Rheingau, has experienced more severe drought events during the last decade, primarily due to increased evapotranspiration connected to higher temperatures but also decreased precipitation (Tissot et al., 2020; van Leeuwen et al., 2019). Calculations predict that 10-30% of the total cultivated area of Rheingau will be under drought stress in 2041-2070 (Hofmann et al., 2021). Grapevine bloom and grape ripening favour dry conditions since rainfall can delay or inhibit the pollination of grape flowers and therefore impact the final yield. On the other hand, excessive precipitation during ripening leads to higher water uptake by the vines, further creating a risk for grapes to split (Neethling et al., 2017).

W2 explained how Rheingau doesn't experience snowy winters anymore. This impacts the overall water balance in the region as snow would usually melt slowly, and thereby water would fill even the deepest soil layers. W2 further acknowledged that the loss of rain during the past three years equals the amount of rainfall during one average year. Recently very dry years were experienced in 2018 and 2019 (W3). Water shortage impacts especially young vines since their root system is not fully developed, and therefore, under water shortage, young vines can dry out or even die (W2). Increased occurrence of extreme weather such as heavy rains has led to a greater risk for erosion, particularly on steep slopes (W1, W2 & W6). Another negative impact of excess water, especially during ripening, is the risk of grape damage through bursting, leading to yield losses and increased disease pressure (W6). This is in line with Neethling et al. (2017).

5.1.3 Changes in the occurrence of spring frosts

The higher seasonal temperature during the beginning of the phenological cycle affects the timing of budbreak, posing a greater risk for buds to be negatively affected by late spring frosts (van Leeuwen et al., 2019; Naulleau et al., 2021). Rheingau has not faced any severe frost damage during the past 30 years, mainly because of the location close to the Rhine river and the topographical features in the form of slopes that enable cold air to drain off from the valley. The occurrence of spring frost events at budbreak may increase in Germany in the future due to climate change since budbreak can advance around one month in the future (Tissot et al., 2020; Leolini et al., 2018).

Temperature increase connected to shiftments in phenological stages was highlighted by W2, who also acknowledged the increased risk for future frost related to the earlier onset of the growing season. The steep slope landscape explains why Rheingau, at the moment, does not suffer extensive spring frosts.

5.1.4 Pests and diseases

Recently, climate change has increased the risk for downy mildew in Rheingau, and in the future, other pests and diseases such as black rot and black wood disease might reach Germany (Tissot et al., 2020). Consistently, W5 mentioned how increased humidity last year led to a greater risk for downy mildew. Additionally, W1 explained how warmer winters had increased the amount of pests and little insects on vineyards, causing damage to vines. An example of this is mice, whose population is normally controlled by frost (W2). New pests and diseases are expected to come from Spain, France, Italy, and Asia due to warmer temperatures (W2).

5.2 Climate change: perception, vulnerability and risks

5.2.1 Personal perception of climate change and perceived vulnerability

All interviewed winegrowers clearly stated that climate change is definitely happening and has multiple impacts, as described above. Vulnerability on vineyards is experienced in numerous ways. The soil was named to be one vulnerable element of the vineyard, especially in relation to water holding capacity under future climatic conditions (W1 & W6). Water holding capacity of different types of soils in the future is concluded by W4: "If you have soils that could keep water, save more water, they will be the winners. And if you have sandy or pretty stony soil, they are going to be more of the losers". Since the common soil type in Rheingau consists of slate and gravel, this suggests that winegrowers will experience vulnerability to climate change due to the weak water holding capacity of the soils. As the most common variety in Rheingau, Riesling itself was experienced to increase the overall vulnerability of viticultural practices among interviewees (W1 & W4). Grapes being sensitive to sunburns was mentioned by W2 as another source of vulnerability. The main concern of vulnerability is young vineyards, as water deficit and heat stress reduce the young plants' capability to grow strong and deep roots (W2, W3 & W5). Therefore, the first three years after planting are the most critical and most vulnerable to extreme weather (W2).

Vulnerability is experienced to mainly target the biophysical elements of the vineyards, such as soil conditions and vines. The different aspects of vulnerability are also interrelated. For instance, soils' decreasing water holding capacity under future climatic conditions also pose further vulnerability to the survival of young vineyards. Therefore, understanding the complexity of the vulnerability of a system is vital, even though various vulnerability features can be defined within viticultural systems.

5.2.2 Perceived risks

According to interviewed winegrowers, one of the biggest risks is the occurrence of extreme weather events, such as hail storms and heavy rains (W3 & W6). W6 further pointed out the risk for erosion due to extreme weather. Overall, the uncountability of extreme weather events is seen as a risk (W5). Last year 50% of the shoots died due to a hail storm in June on the vineyard of W3. This directly impacts the quantity and quality of the harvest (W1 & W2). Riesling's suitability for Rheingau is questioned, and future climatic conditions may pose greater risks for farming possibilities for Riesling (W1). The harvest quality impacts the wine profile, which further poses difficulties and risks in selling wine and retaining cost-efficiency (W2). W3 has a similar experience of risks regarding the typicity of the wine due to climate change, but at the moment the risk is acceptable according to the winegrower, since the wines from lower yields can be sold at a higher price. Similarly, W5 experiences climatic risks as tolerable since they can be kept within reasonable limits through investments in manpower and overall flexibility in everyday work. However, W5 also highlighted the importance of understanding climatic variations even from one year to another and being able to reflect on adaptation measures regularly. The winegrower further explained how one's mindset can become a risk to climate adaptation: "If we start thinking black and white, we will limit ourselves" (W5).

W2 mentioned risks regarding planting new vineyards and replanting parts of older vineyards. With irrigation, risks related to heat stress and water deficit can be kept tolerable. Still, without any adjustments, climate change can pose intolerable risks for especially young vineyards in the future (W2). On the other hand, an optimistic mindset was discovered in the interviews. W5, for example, stated that climatic risks are manageable, but the willingness to deal with them must exist. W2 concluded: "We are not completely helpless, but it's getting trickier and more complicated." Moreover, trust in vines' natural capacity to adapt to changing conditions when it comes to variations in temperature and precipitation is a factor that gives hope to winegrowers (W3, W4 & W5).

To summarise, risks are experienced individually among all winegrowers, as personal perception and vineyard characteristics influence the experienced climatic risks on the vineyard level. Risks are mostly perceived as tolerable since adjustments in the form of adaptation measures can be made. Some winegrowers are more optimistic about future risks than others, which speaks of the importance of reflecting on risks from context-based and personal perspectives. However, risks related to Rieslings' suitability in Rheingau under future climatic conditions are a relevant concern among winegrowers since it is in line with Neethling et al. (2019) and Santos et al. (2020) about future projections of climatic suitability for different grapevine varieties.

5.3 Climate adaptation measures

All six Rheingau winegrowers were aware of viticultural adaptation measures and had implemented multiple ones on their vineyards. As presented earlier, adaptation measures can be short-term and long-term in their character (Santos et al., 2020). In line with the conceptual framework on viticultural decision-making by Neethling et al. (2017), results are furthermore analysed, reflecting the overall adaptation work, including the influence of adaptation constraints and opportunities in the dynamic decision-making processes. To form a starting point for this section, W3 stated: "It's just the fact that you can't work like you worked 20 years ago".

5.3.1 Short-term measures

All the winegrowers brought up ground management as a short-term practice. The use of cover crops, also known as greening, makes soils healthier when weeds, grass, and flowers are grown in between the rows on the vineyard. The main idea of cover crops is to keep the soil cool, especially during warmer temperatures (W3 & W4). When soils are covered with crops, sun exposure on soils is reduced, and risks for soils to dry out decrease (W1). Another aspect of greening is the decreased transpiration from the covered soils (W5 & W2). W2 further explained another benefit of cover crops as a climate adaptation measure: vines have to compete over the water resources in the soils, which encourages vines to push their roots deeper and deeper. In addition, cover crops increase the water holding capacity of the soils (W6). This is beneficial under future climatic conditions since droughts and water shortages are likely to become more frequent (Hofmann et al., 2021). Consequently, healthier soils contribute to vines' capacity to withstand water shortage and heat, as W6 explained: "It's like a human, when a human lives more healthier it is stronger against some diseases." Regarding the risk for erosion, cover crops are used to better stabilise thin soils, especially on steep slopes (W2). W5 pointed out how cover crops on flat vineyards are used to lift up the nutrition components of the soil to create more diverse soil life and to further strengthen the vines already from the roots. Finally, mulching (the use of compost on the soils) is used by W6 to improve soil health.

Even though cover crops are viewed as a short-term adaptation measure by four out of six winegrowers, W5 and W6 classified greening as a long-term practice. This can be explained as cover crops are usually seasonal, some crops thriving up to 3 years, and therefore the adaptation is focused on a short-term time scale. On the other hand, cover crops improve the water holding capacity of the soil together with nutrient matter, which has long-term effects on the overall health of the vineyard. To conclude, the implementation of adaptation measures can impact both annual and perennial viticultural practices simultaneously (Neethling et al., 2017).

Another short-term adaptation measure used by three winegrowers was canopy management, more precise adjustments to leaf coverage of the vines (W2, W3 & W4), and adjustments to the length of the shoots (W2). Both practices aim to reduce sunburns on the grapes. There are two approaches to work with leaf coverage and sunburns. W2 chose not to take off some leaves from the vines in order to maintain leaf coverage as natural sun protection for the grapes. On the other hand, W3 and W4 favour leaf thinning since sun exposure on grapes early in the growing season creates a substance that hardens the grapeskin and further protects against sunburns. In addition, W2 explained how cutting the shoots a little bit shorter decreases the overall evaporation of the vines since the number of leaves is reduced. This contributes to the vines' capacity to cope with droughts and water deficits.

Overall, climate adaptation measures can be used differently based on winegrowers' personal beliefs and experiences with climate. Additionally, place-specific and context-dependent factors such as farm characteristics influence the way adaptation measures are used (Garini et al., 2017; Mosedale et al., 2016). This is evident from the interview findings in Rheingau since cover crops can be used either on every row or every other row, based on vineyard structure and soil conditions. The type of applied canopy management is also closely guided by the need for improvements on specific vineyard spots.

5.3.2 Long-term measures

Compared to short-term adaptation measures, a greater variety of long-term adaptation measures were found amongst the Rheingau winegrowers. Site selection and vineyard structure influence the vineyard's adaptive capacity where winegrowers' decision-making for the locations best suitable for the future as well as the design of the vineyard play a critical role (Neethling et al., 2016). The relocation of vineyards is used as an adaptation measure by W2. W2 explained how Riesling requires a cool climate and therefore planting Riesling at a higher altitude is a coping mechanism for climate change. Riesling was previously planted close to the Rhine, but since the river functions as a heat collector, the temperature up on the hill is 1°C cooler compared to the river valley, also due to an elevation difference of 80-100 metres (W2). W4 sees a possibility of using this adaptation measure in the future to secure the viability of Riesling.

In order to prevent erosion on steep slope vineyards due to heavy rains, terrace vineyards were implemented by W1 and W2. Besides protection against erosion, this type of vineyard structure more efficiently collects and holds water, as explained by W2: "Each row is like a stair step, and all the water can stay in the flat area, and it does not get washed out. It's important to collect every drop of rain when the rain comes". Additionally, canopies on terraced vineyards have better airflow compared to traditional vineyards. This further decreases the risks of grape rot during harvest season (W2). Vines can be encouraged to develop deeper roots by regulating the planting density of the vines (W1). A shorter distance between vines forces root systems to grow deeper in the soil, further increasing the vines' capacity to cope with water deficit (W3).

As a response to water shortage, irrigation is used on three vineyards. W2 and W5 clearly stated that only young vineyards are minimally irrigated during droughts. The purpose of irrigation is to save the vines from dying, not secure yield (W2). W2 collects rainwater during the winter months in big storage tanks, whereas W1 uses water from the Rhine river and groundwater. The source of irrigation water is debated since W2 for instance is clearly against using the river water as the water level in the Rhine has been extremely low during the past five years. When it comes to the other three winegrowers, W3 plans to implement an irrigation system on steep slopes once it is time to replant those vineyards. W4, in turn, removed all irrigation seven years ago to encourage young vines to grow deeper roots in the absence of watering. W6 had a clear stance against irrigation, as irrigation creates problems for root structures as vines would get used to watering. All in all, irrigation as an adaptation measure received contradictional opinions among the Rheingau winegrowers.

Finding the most suitable rootstock for future climatic conditions is an important aspect according to W1, W2, and W3. During the past ten years, W2 has used rootstocks for new plantations that quickly develop deep roots. Also, W3 highlighted the importance of choosing the best possible rootstock and clone: “if you plant a new field, you should already think about how it will be in 30 years”. In addition, changing grape varieties to better resist warmer and drier conditions has led to Cabernet Sauvignon and Merlot being grown for additional red wine and Chardonnay for additional white wine for the past 20 years (W2). On the contrary, W6 didn’t support alternative grapevine varieties since the winegrower experienced that traditional Riesling and Pinot Noir thrive well in today’s climate. Thus, the choice of new varieties is not an obvious climate adaptation measure among winegrowers.

5.4 Climate adaptation constraints

Biophysical constraints

One of the main biophysical constraints expressed by the winegrowers is the physical location of vineyard spots owned by one winery since vineyards are often spread out, and the distance between vineyards can be several kilometres (W1 & W5). Therefore, applying one type of adaptation measure to all vineyards is not desirable because a range of different varieties together with varying soil types require place-specific climate adaptation even within the vineyards (W1). This underscores the general point that climate adaptation must be applied based on contextual, place-specific factors, including farm characteristics (Neethling et al., 2017).

In Rheingau, general irrigation systems don't exist, which further complicates the implementation of irrigation systems (W2). Problems with generating water and dilemmas around the origin of the water create constraints for winegrowers (W2 & W3). W5 mentioned that even though they have been working on the implementation of an irrigation system for 12 years, the structure of a complete irrigation system is not yet in place. Rheingau doesn't have big natural water reservoirs that could be used for irrigation (W2). Further, vineyards being located in natural heritage areas restricts water collection, for instance, with big water pools (W5).

Restructuring of vineyards entails substantial workloads (W1), and some of the steep slopes areas are not cultivated since machines are applicable, and therefore a lot of handwork is required (W2). W5 highlighted how it will be impossible to relocate all vineyards to higher elevation levels in the future simply because of the limited space on steep slopes. Consequently, the restricted area of suitable growing space can develop into a hard limit for adaptation in the future.

Governmental and institutional constraints

Law regulations and general German bureaucracy hinder the implementation of irrigation systems, choice of rootstock, as well as varieties (W1, W2 & W5). For instance, getting permission from the government to use new rootstocks takes several years (W2). Furthermore, W2 stated regarding the planting of new varieties: " It's hard in Germany where everything is regulated, and I think 95% of the varieties that are available worldwide are not allowed to be planted in Germany". This indicates that the regulatory framework currently creates soft adaptation limits, as defined by Klein et al. (2014).

Financial constraints

Regarding the financial constraints on the vineyard level, W1 and W4 explained how costs for all inputs for running a vineyard are increasing, consequently leaving less capital for climate adaptation. For instance, redesigning vineyards into terracing systems is three to four times more expensive than planting a normal vineyard (W2). Another financial aspect is planting density since terraced vineyards can carry up to 3500 vines/hectare, compared to 5000 on flat vineyards (W2). This influences overall yield and final income. The use of insurance to cope with losses from extreme weather is often too expensive to be purchased by winegrowers (W3). Another point is that when investing in climate adaptation measures, immediate positive effects are seldom experienced since it can take 20-30 years to see the outcome (W1). W4 further summed up: "you can change a lot, but it costs a lot of money," meaning that financial capital is the biggest hindrance to adaptation.

Economic constraints

Regarding economic constraints on the national and global level, W1 mentioned that the wine market is already competitive, and coming up with profitable, new styles of wine is difficult. This becomes a constraint to using new varieties. W2 added that wine itself, as a luxury product, is more challenging to sell than everyday needs, thus, adjustments to wine profiles entail an economic risk.

Social and cultural constraints

The main social and cultural constraints regarding the implementation of new varieties are the customers' preferences regarding the typicity of the wine of a given region and its unique terroir. Changing traditional varieties such as Riesling to more climate resistant ones is not straightforward, as W3 put it: "it's not tolerated or accepted that we would do something unusual for the Rheingau region, so the pressure from the customer is too high to do it." Similarly, W2 explained the dilemma with consumption habits: "In the end, if a customer wants a Riesling from the Rheingau region, he doesn't want a Chardonnay from the Rheingau region." Loss of yield quality and quantity due to climate change can be modified by selling wine for a higher price, but customers' unwillingness to pay more can create a social constraint (W2). W6 expressed the problem of finding clients willing to pay more for a bottle since this type of customer is often a niche. Nevertheless, selling wine for a profitable price is the way to maintain wineries' financial sustainability. Therefore, customers' preferences and consumption habits can become a hard limit for the adaptation measures.

Social constraints were also experienced regarding irrigation systems. Since grapes are not a fundamental crop for humans, nor is wine an everyday necessity, scarce freshwater resources should be allocated to vital agricultural sectors (W2, W3 & W5). W6 explained: "wine isn't as necessary as your daily bread," which hinders the implementation of irrigation systems (W2). To avoid social conflict on resources, W5 irrigates only the young vineyards. In addition, irrigation in Rheingau doesn't receive a big general interest which hinders the implementation of irrigation on a bigger scale (W5). Implementation of irrigation in viticulture can be maladaptive since water vulnerability might increase in other agricultural sectors if grapevines are irrigated. Hence, social values and competing priorities regarding water resources connect to the overall distribution of vulnerability and adaptive capacity among different actors and sectors in society on a national level. Since other agricultural sectors and their vulnerability to climate change are prioritised over viticulture, the implementation of adaptation measures on vineyards depends mostly on individual winegrowers.

Human resource constraints

Uncertainties regarding future climatic risks and vulnerabilities due to lack of information about climate change impacts in the future are explained by W4: "It's pretty difficult to talk about something what nobody actually knows what is really coming, that is the problem." In addition, questions regarding the functionality of already implemented adaptation measures in the long run and difficulties in choosing the 'right' adaptation measures today were the only human resource constraints identified among winegrowers (W1).

5.5 Climate adaptation opportunities

Learning

Learning experiences are one of the main opportunities and enabling factors that encourage winegrowers to use adaptation measures. W1 addressed: "We don't have 30 years' time to change everything, it's 15 years or 10 years, but we need the information. Practice and practice and practice". Therefore, through learning-by-doing, winegrowers can find solutions and the best suitable adaptation measures to climate change impacts: "You need to get the bad impacts that are not so good, because we have to work them out" (W1). W4 and W5 highlighted that it is also in farmers' attitudes to gain experience through trial and error. W3 concluded that getting experience with climate change and the different adaptation measures increase every year since new strategies and methods are tested every season.

Capacity building

Concerning research, data, education, and training, W5 explained that there is a lot of potential knowledge about climate change and its impacts, but since the winegrowing sector is so specific, the knowledge transfer from science to practice is not always that simple. Many things are starting to develop for viticulture, but "there is a big gap between actual and existing knowledge on how to better deal with situations" (W5). Experts and researchers at Geisenheim University can deliver education about climate change impacts to winegrowers and thereby increase vineyards' capacity to adapt to climate change (W2 & W4). When several stakeholders are connected through various networks, change on the vineyard level can be faster (W1). This type of development of social capital can boost the implementation of adaptation measures (Klein et al., 2014). On the other hand, W1's vineyard has a reputation for being the leader in education regarding climate change adaptation measures for smaller wineries, highlighting the importance of education and training between vineyards. Sharing knowledge from winegrower to winegrower is only seen in a positive light, with no signs of competition. This is in line with Nicholas and Durham (2012).

Additionally, the development of human capital, knowledge, and experience on an individual level enables the adaptation work by winegrowers (Bowen et al., 2012). For instance, W2 and W3 have studied at Geisenheim, and W2 further explained that many young winegrowers have knowledge about climate change impacts and can therefore work accordingly. Thus, the young generation of winegrowers gives hope for future adaptation work. W6 expressed how the type of farming was changed ten years ago from conventional to organic due to personal disapproval of conventional practices. The winegrower experienced that changing practices also contributed to reducing climate change impacts. This further connects to the overall idea of conserving the vineyards for the future so that wine can be produced even in 50 years, not just today (W1).

Innovation

Technological change can enhance climate adaptation since solutions for water storing could enable more extensive use of irrigation in Rheingau (W2). Various companies offering technological solutions to canopy management, e.g., leaf thinning, give possibilities for winegrowers to try out new innovations that can guide future adaptation work (W3 & W4).

Awareness raising

Lastly, positive stakeholder engagement from the government can enable more comprehensive use of various adaptation measures, such as rootstocks and new grapevine varieties. To date, laws have been hindering flexible and quick adaptation work. According to W1, the German government has acknowledged the problem with time-consuming bureaucracy regarding the allowance of multiple adaptation measures, which hopefully generate faster institutional processes in the future.

In contrast to adaptation constraints, all adaptation opportunities besides technological innovation consider social context and human factors. This underscores winegrowers as the primary agents for climate adaptation, and personal knowledge and experience through learning are the most fundamental factors that enable climate adaptation on the vineyard level. Knowledge transfer between important stakeholders, such as universities and government, highlights the importance of dynamic networks that can provide new insights and information to adaptation work and secure the judicial perspective of various adaptation measures in Rheingau.

6 Concluding discussion

Drawing from the analysed research questions 1, 2, and 3 in the results and analysis section, concluding remarks about the adaptive capacity of studied vineyards are presented below.

Experienced and projected climate change impacts by Rheingau winegrowers were fully in line with scientific research, identifying that studied winegrowers have a deep understanding and experience of changing climatic conditions in Rheingau. Further, adaptive capacity takes systems' vulnerability to climate change into account, evaluates risks, and finally reflects on adaptation constraints and opportunities that influence how well a system can adapt to climate change (Klein et al., 2014; Reidsma et al., 2010). Raymond and Spoehr (2013) found that acceptance and acknowledgement of human-induced climate change encourage winegrowers to implement adaptation measures. This type of behaviour pattern was observed among the Rheingau winegrowers, as they all undoubtedly recognised the existence of climate change and further acknowledged adaptation measures to be the coping mechanisms to climate change. Additionally, Fourment et al. (2020) found in previous research that different vineyard scales create various types of perceptions of climate change among winegrowers. This is inconsistent with the findings from the interviews, as neither the size of the vineyard nor other characteristics of the winegrower or vineyard had any impact on how climate change was perceived. All respondents had a strong perception of climate change, and no sign of climate scepticism was observed among Rheingau winegrowers. Therefore, winegrowers' personal perception of climate change in the Rheingau wine region encourages adaptation work instead of creating a constraint for it.

Besides the personal perception of climate change itself, winegrowers' perception of vineyards' vulnerability and risks connected to climate change influence the overall adaptive capacity (Klein et al., 2014; Mosedale et al., 2016). Farmers and winegrowers who have perceived more climatic stresses in the past are more prone to implement adaptation measures (Talanow et al., 2021), as a higher perceived risk to climate change leads to a higher motivation to adapt (Osberghaus et al., 2010). In line with this, several winegrowers in Rheingau highlighted that adaptation measures should be used more extensively under future climatic conditions. Santos et al. (2021) acknowledge that winegrowers generally tend to prefer short-term practices to long-term ones due to greater financial investments in the latter ones. However, this is not in line with the findings from this study, as the interviewed winegrowers in Rheingau use long-term measures more generously than short-term actions. Furthermore, short-term measures, such as cover crops, can be seen as long-term climate adaptation measures since their effect is not restricted to one season. Combining diverse and comprehensive adaptation measures is desirable since only in doing so contextual and place-specific climate adaptation can be achieved (Neethling et al., 2017). Accordingly, the Rheingau winegrowers highlighted the importance of avoiding to use just one overall adaptation measure but instead creating distinctive adaptation strategies for different cultivated spots within a vineyard.

Overall, the majority of risks related to climate change were categorised as tolerable among studied winegrowers. This can be explained by the findings from Talanow et al. (2021), as particularly long-term risks are often experienced as tolerable since time will allow the possibility to implement sufficient adaptation measures. Nevertheless, a clear consensus on what types of adaptation measures are required in the future is lacking among the Rheingau winegrowers, mostly due to uncertainty about climate change impacts in the long run. This underscores the importance of shared knowledge between winegrowers and other stakeholders in viticulture, which can guide the autonomous decision-making on the vineyard level, increasing the overall adaptive capacity (Nicholas & Durham, 2012; Neethling et al., 2017; Reidsma et al., 2010). Therefore, policy-making should consider winegrowers' personal perceptions together with adaptation constraints and opportunities that lie behind decision-making processes. Only then can a sustainable and effective adoption of suitable viticultural practices be enhanced (Garini et al., 2017; Reidsma et al., 2010). Networks for experience sharing between winegrowers are already created in Rheingau to gain knowledge about adaptation measures on a regional level and further support other winegrowers in their adaptation work. Furthermore, according to the Rheingau winegrowers, there is an evident need for more scientific research in local settings to boost climate adaptation in viticulture.

Interestingly, all constraints mentioned in the interviews were connected to long-term adaptation measures. The high cost of adaptation measures, laws, social values, and vineyard design were the most definite adaptation constraints. Especially irrigation raised conflicting standpoints among the Rheingau winegrowers due to scarce water resources in the region but also nationally. In addition, the grapevine was seen as an 'unnecessary' crop compared to other fundamental crops for human survival, and therefore the use of irrigation was questioned among interviewed winegrowers. Additionally, Fraga (2020) describes how water resources for irrigation are projected to become even more limited in the future. This creates a social conflict that draws further concerns and prioritisations between different agricultural sectors in society. Overall vulnerability and importance of different sectors are thereby evaluated, which can lead to viticultural practices receiving less attention when it comes to climate adaptation. Implementation of adaptation measures consequently largely depends on individual winegrowers. Although wine is not considered vital for human survival, winegrowing serves as one of the main socio-economic sectors in Rheingau (Hofmann et al., 2021), meaning that grapevines are fundamental crops for people working in viticulture. Therefore, the viticultural sector in Germany and globally deserves to be focused on when it comes to climate adaptation. If not, a key socio-economic sector, also from cultural and historical aspects, is at risk of being lost.

Regarding the local vulnerability aspect of vineyards in Rheingau, it is crucial to recognise how different parts of vulnerability, such as soils and vines, are closely interconnected. This means that the vulnerability of vineyards is multidimensional. Although different vulnerability features can be named within a vineyard, vulnerability should be approached at the system level. This is central for winegrowers' dynamic decision-making processes regarding the use of optimal adaptation measures in order to reduce the overall vulnerability (Neethling et al., 2017; Reidsma et al., 2010). Regardless of uncertainties about future vulnerabilities on the vineyard level, at the moment, all interviewed winegrowers experienced a good adaptive capacity on their grape growing sites.

Considering that climate adaptation is contextual and place-specific (Merloni et al., 2018), more research on local settings at a vineyard level is recommendable. As previous research has not focused on exploring the local adaptive capacity and further mainly ignored the limitations of different adaptation measures (Naulleau et al., 2021), future research should include these aspects more deeply. Furthermore, as mentioned in one interview, knowledge transfer from scientific research to practical adaptation measures for winegrowers is a key in order to enhance overall climate adaptation in viticulture. Therefore, future research should focus on generating more applicable methods for winegrowers while taking into account winegrowers' perception of climate change and adaptation measures themselves.

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8 Appendices

Appendix 1: The interview guide

This interview focuses on adaptation measures on grapevine farming, excluding winemaking in the winery. Everything said in this interview will be completely anonymous. Thank you again for taking your time for this interview!

Some concepts that are used in this interview:

Adaptation measures in this interview mean strategies and actions that can be implemented on vineyards to improve adaptation to climate change.
Adaptation constraints, also known as barriers and challenges, are factors that hinder or make the implementation of adaptation measures difficult.
Adaptation opportunities are factors that enable and promote the implementation of adaptation measures. Constraints and opportunities can be varying in their nature and therefore one of the main focuses of this study is to understand what types of factors hinder but also enable viticultural adaptation to climate change.

Background questions

1. How long have you worked with viticulture?
2. How old is your vineyard?
3. How many hectares is your vineyard?
4. What varieties are you growing?
5. What are the main features of your vineyard (elevation, slope, aspect etc.)?
6. Do you work with conventional, organic or biodynamic practices?

Climate change: perception, vulnerability and risks

7. What is your perception about climate change and its impacts?
8. Have you experienced climate change impacts on your vineyard?
9. How vulnerable do you think your vineyard is to climate change? What elements of your vineyard are especially vulnerable?
10. What type of risks are you facing and/or will face due to climate change? Are they acceptable, tolerable or intolerable risks?

    (**acceptable** risks do not require any additional climate adaptation efforts,
    tolerable risks are situations where adaptation efforts are needed to keep risks within reasonable levels,
    intolerable risks are risks that lack practical and affordable adaptation measures and therefore create losses to the vineyard)

Climate adaptation measures: opportunities, constraints and limits

11. Are you aware of adaptation measures in viticulture?
12. Have you implemented adaptation measures in your vineyard? If yes, which ones?
    - short-term (seasonal)?
    - long-term (decadal)?

13. In case you haven't implemented adaptation measures, are you planning on doing so?

14. What constraints/barriers/challenges do you experience to hinder the implementation of different adaptation measures? Are they:
    - ecological (including physical constraints such as farm structure and biological constraints for example phenotypic variation in grapevines)
    - financial constraints (cost for different adaptation measures)
    - social and cultural constraints (including knowledge, awareness, values, sense of particular place)
    - or governance and institutional constraints?

15. What are the main adaptation opportunities that encourage you to implement and use adaptation measures on your vineyard? In other words, which factors enable the implementation of adaptation measures on your vineyard? (Some examples: knowledge, experience, technological advantages)

16. Are there any measures that you would have liked to use but they have been completely impossible to implement?
    - What is the reason behind it?
    - Have you experienced any consequences due to lack of adaptation measures?

17. What could help to implement more adaptation measures in viticulture?

18. Reflecting on the above stated questions, how well can you adapt your vineyard to climate change?

19. Is there anything else you want to add or elaborate further?

20. Is there anyone you know who would be interested in participating in an interview?

Appendix 2: A consent to participate in an interview and to be recorded

You are invited to participate in an interview which focuses on winegrowers' perception of climate change and experienced impacts on vineyards. The goal of this study is to understand winegrowers' experience of different adaptation measures and what constraints as well as opportunities enable and hinder the adaptation work in the Rheingau wine region. I believe this study will further contribute in finding solutions to climate adaptation work in viticulture. Interviews are going to be recorded if you consent below. Data from the interviews will be stored securely and Viveka Vainio will have the only access to recordings. All participants are anonymous in this study.

Your participation is completely voluntary and you have the right to withdraw your participation at any time. You also have the right to decline to answer questions you do not feel comfortable with. Interview will take approximately one hour.

In case you have questions regarding this research, please do not hesitate to contact me by phone or email. Tel: +358442004723, email: vivekaeve.vainio@gmail.com

1) I give consent to be recorded during the interview: Yes _____ No ______
2) I agree to be quoted directly, but being anonymous: Yes _____ No ______

If you like to have a copy of the thesis, please write your email address below:

Please sign before the interview. Thank you again for taking your time to participate in this study!

Name of the participant		Name of the interviewer	
_______________________		_______________________	
Signature of the participant	Date	Signature of the interviewer	Date
_______________________	______	_______________________	_______