General introduction

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Climate change is a reality that impacts all of us and is changing our way of life on Earth. The findings of each successive IPCC[1] assessment report – the most recent being the sixth – are becoming increasingly alarming, hence the need to act with the utmost urgency (IPCC, 2023). Agriculture is on the front line, both as a major emitter of greenhouse gases and an industry highly impacted by its dependence on the climate. These links to the climate are of vital importance to the French viticulture and wine industry. Historically, they are in integral part of the concept of terroir and play an important role in the location of vineyards, the choice of grape varieties and practices, the definition of wine qualities, and the organization of wine markets (Dion, 1990). Climate change is upsetting a delicate balance that has developed over time and is part of the very foundations of an activity that has such a special place in the French economy and society (Ollat *et al.*, 2020, 2021). This poses a major challenge for everyone involved in the industry, from winegrowers to wine consumers, not to mention the researchers who produce knowledge about its various components.

The heatwave that hit France in 2003 brought home the challenges posed by climate change, leading researchers to begin looking into it the following year (Ollat *et al.*, 2020), with stakeholders in the viticulture and wine industry either supporting their research efforts or taking action themselves to assess their carbon impact. Meanwhile, wider scientific and political discussions at international conferences such as the Conferences of the Parties (COP) quickly established that measures to reduce greenhouse gas emissions would not be enough to curb climate change and that adaptation was becoming a key issue for agriculture and the food industry (Soussana, 2013). In 2011, for example, the French National Institute for Agricultural Research (now INRAE) set up a multidisciplinary framework called the Adaptation to Climate Change in Agriculture and Forestry (ACCAF) Metaprogramme to support projects looking into climate-change adaptation in agriculture and forestry (Caquet, 2017). Scientists involved in viticulture and wine, some of whom were already working on climate change projects, took the opportunity to put forward a project entitled LACCAVE: *Long-Term Impacts and Adaptation to Climate Change for Viticulture and Enology*. The main aim was to pull together all relevant research being conducted in France and to make the results more readily available to industry stakeholders (Ollat and Touzard, 2014). Published after 10 years of activity (and two IPCC reports), this book takes stock of the work conducted to date, offers a state of knowledge on the subject and reports on the approaches that have moved industry

1. Intergovernmental Panel on Climate Change, a body that advances knowledge on climate change.

stakeholders to action. It aims to appeal to a large number of readers, in keeping with the spirit of participation that has driven LACCAVE since its inception. It is divided into two main parts. The first comprises nine chapters describing the impacts of climate change on grapevine, soil and wine quality, followed by technical and geographical adaptation levers: the development and selection of new varieties, vine management, water management, oenological solutions and reference to climate variability in a given area for vineyard reorganization. The second part is made up of seven chapters that explore how industry stakeholders work with researchers and use the levers available to develop knowledge and strategies: the perception of impacts among winegrowers and consumers and the role of professional organizations, research, training and participatory approaches leading to the emergence of solutions at local level, the design of new winegrowing systems, and the creation of a national adaptation strategy. The two parts put forward a wide range of scientific contributions, with particular attention paid to the methods employed. Each chapter features in-depth details on experiments, systems, results and actions in special text boxes.

Changing climate a cause for concern

Since the advent of the twentieth century, the atmospheric concentration of CO_2 has risen by 40% (reaching 419 ppm in 2023), with almost half of this increase occurring in the last 30 years. As a result, air temperatures in France have increased by an average of nearly 1.8°C year on year, a process that has gathered pace since the 1980s, with every year since 1990 being warmer than the average since 1900, and the warmest years being 2014, 2018, 2020, 2022 and 2023 (Météo-France, 2024, figure Intro-1A). This in turn has led to an increase in soil temperatures up to a depth of 50 cm (Schultz, 2022). However, annual rainfall has shown little change, increasing slightly in the north of France and falling in the south, with more significant decreases depending on the season and region. In the Mediterranean region, the number of cycles in which winter precipitation (when soil water is recharged) fell below 200 mm increased during the period 1990–2021 (table Intro-1). Furthermore, an increase in potential evapotranspiration brought about by rising temperatures has been recorded at vineyards located at various latitudes across Europe (from Avignon to Geisenheim in Germany), although this is not a systematic occurrence (Schultz, 2017).

Compared to the 1976–2005 period, warming is set to continue without any significant difference between the various emissions scenarios that may play out between now and 2050 (+1°C to 1.5°C). In the most pessimistic scenario, temperatures in south-eastern France could rise by more than 5°C by the end of the twenty-first century, with a spectacular increase in the number of heatwave days (Corre *et al.*, 2021; figure Intro-1B and figure Intro-2). Precipitation trends cannot be predicted with any great certainty (Zito, 2021; Ollat *et al.*, 2021). Nevertheless, longer droughts are expected in the years ahead, particularly in southern and western France (Corre *et al.*, 2021). Some Europe-wide simulations point to a 10%–30% increase in actual evapotranspiration as early as 2050, with a water balance (rainfall minus potential evapotranspiration [PET]) that could fall by as much as 120 mm in southern regions (Cardell *et al.*, 2019). These projections are confirmed by the work of Zito *et al.* (2023), which provides the most recent simulations of climate and bioclimatic indicators for 21 French winegrowing regions on an 8×8 km grid. Any rise in temperature

Table Intro-1. Median winter (October to March) precipitation values over the historical period at French winegrowing sites and differences between the period before 1990 and the last 30 years. According to N. Saurin, AgroClim-INRAE data.

	Start of the series	Median […–1989] Recharge (mm)	Median [1990–2021] Recharge (mm)	Difference between [1990–2021] and […–1989] Recharge
Marseillan-Plage	1956	349.4	292.5	**−56.9**
Gruissan	1962	403.6	319.9	**−83.8**
Colmar	1973	213.2	233.3	20.1
Mauguio	1956	415.2	320.0	**−95.2**
Montreuil-Bellay	1977	334.8	308.5	−26.3
Fagnières	1971	312.3	295.1	−17.2
Avignon	1968	362.2	354.0	−8.2
Villenave-d'Ornon	1961	518.7	504.8	−14.0

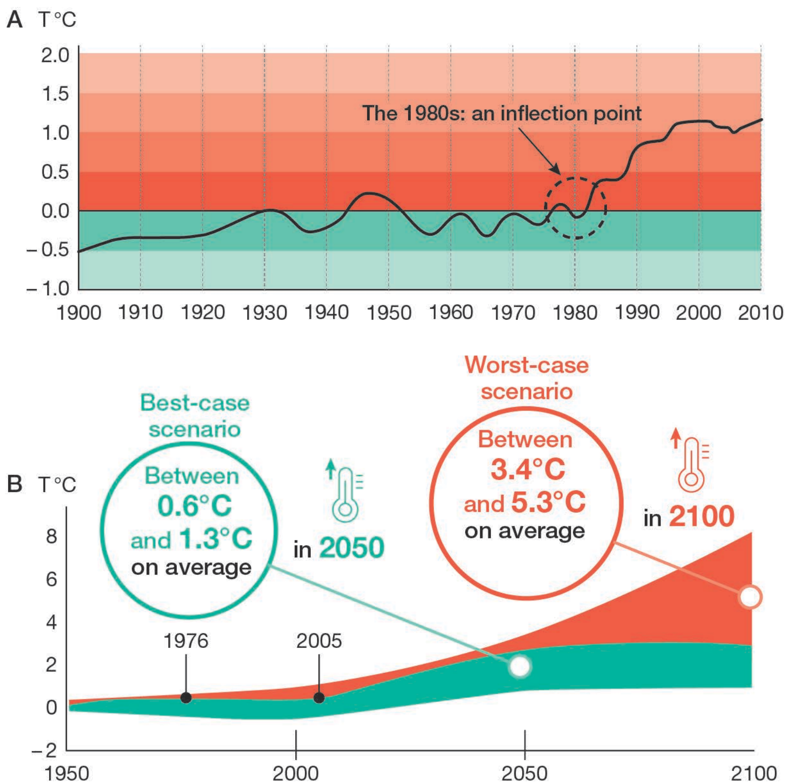

Figure Intro-1. Variations of average air temperature in France since 1900 (A) and simulated figures for the twenty-first century (B). The temperature has risen by almost 1.8°C over the last century and will continue to rise at a variable rate depending on greenhouse gas emissions scenarios. Increases are expressed in relation to the reference period (1976–2005).

also increases the frequency and intensity of extreme events such as storms and heat-waves, with impacts including the increased risk of fire, the destruction of infrastructure and ecosystems, and negative effects on human health (IPCC, 2023). These last few years are a perfect illustration of the gravity of the situation, both in France and globally.

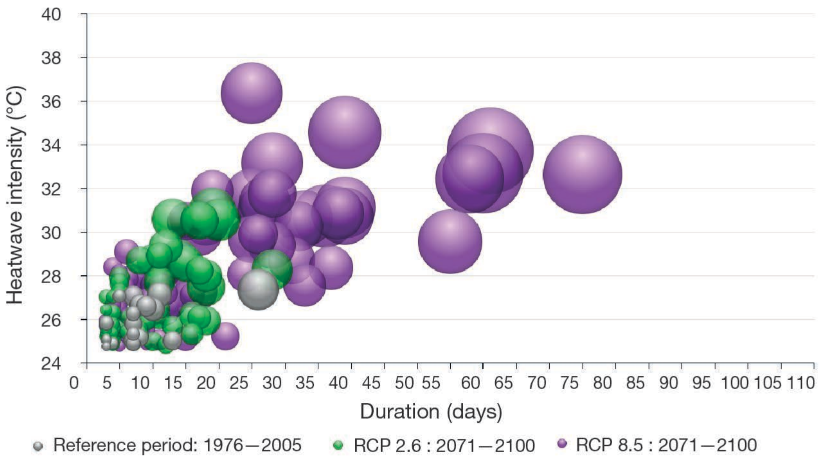

Figure Intro-2. Observed (1947–2018) and simulated (through to 2100) annual heatwave characteristics for different scenarios and time frames. Source: Météo-France.

The consequences in store for viticulture and wine – which have been noticeable since the 1980s – are a cause of great concern to industry stakeholders: harvests occurring up to 20 to 30 days earlier by the end of the twenty-first century (Zito *et al.*, 2023); a possible increase in the risk of spring frosts (Sgubin *et al.*, 2018; Bois *et al.*, 2023); temperature increases during grape ripening, affecting their winemaking potential (Van Leeuwen and Destrac-Irvine, 2017; Van Leeuwen *et al.*, 2022a); changes in the risks associated with diseases and pests, although these remain difficult to predict (Caubel *et al.*, 2014; Bois *et al.*, 2017; Zito, 2021); more frequent and more intense droughts, with an impact on yields (Lebon and García de Cortázar-Atauri, 2014). The current situation and forecasts are concerning for all traditional winegrowing regions, where winegrowers fear for their ability to retain markets and ensure their continuing financial sustainability. In some winegrowing areas, however, these new climate conditions could have less of a negative effect, such as in Alsace (Duchêne and Schneider, 2005) and the Loire Valley (Touzard *et al.*, 2020), at least until 2050. Furthermore, some regions not especially known for winegrowing at this moment in time are showing potential (Ollat *et al.*, 2016b), among them Brittany (Zavlyanova *et al.*, 2023), raising the prospect of a "new viticulture geography" by the end of the century.

The LACCAVE project: a systemic and participatory approach to adaptation

When it comes to exploring the issue of climate change adaptation, the specific characteristics of the viticulture and wine industry make it a unique and interesting subject for scientific research. The importance of wine production to the French economy is the backdrop to that. The industry employs many people directly and indirectly and accounts for a significant chunk of French exports (nearly €15 billion worth in 2022). There is also a cultural side to its status, given its effects on tourism and France's appeal as a destination. The industry is also very well organized and regulated by the system of protected designations of origin and geographical indications, which provides a legal framework encompassing the location of vineyards, winegrowing technologies and practices, and wine quality and markets. The fact that environmental, technical, economic and political factors are closely interlinked means that innovations and the changes needed to adapt to them require an interdisciplinary approach as well as discussions to bring the issues of priorities and coordination within the industry more sharply into focus. The scale of long-term investment, ranging from the vineyard to intangible assets such as a wine's reputation, is so significant that stakeholders need to look several decades ahead into what the future of climate change might hold. Planting a vineyard today involves acquiring the knowledge needed to envisage the wine it could produce in 2050. All these issues combine to make this high added-value industry a model for a pluridisciplinary approach to the analysis of climate change adaptation (Ollat *et al.*, 2020).

LACCAVE brought together a scientific network of 22 laboratories affiliated with INRAE, France's National Centre for Scientific Research (CNRS), and the universities and *grandes écoles* located in the country's main winegrowing regions and covering an array of scientific disciplines – from climatology and social sciences to genetics, physiology, agronomy, oenology and pathology. The network also forged ties with FranceAgriMer, the French National Institute of Origin and Quality (INAO), the French Wine and Vine Institute (IFV), engineers from the country's chambers of agriculture, and representatives of France's main wine trade associations.

The project's scientific objectives were to explore the long-term impacts of climate change (2050) on grapevine cultivation and wine production at a regional level and to acquire knowledge for developing and evaluating adaptation innovations and strategies for these winegrowing areas. In line with the ACCAF metaprogramme priorities, the objectives were also to provide a structure for French research into these issues and make it more visible, the idea being to better respond to demand from industry stakeholders and, in a broader sense, to disseminate knowledge and thereby raise climate change awareness among these stakeholders and society in general.

Over 10 years, LACCAVE met these academic, organizational, expertise-related and developmental challenges thanks to a wide range of initiatives and outcomes. This positive dynamic was made possible by the very duration of the project. Targeted studies into different aspects of adaptation, from planting material to analysis of consumer behaviour, were conducted over a sufficiently long period for a perennial crop and, ultimately, for industry stakeholders to take note of the climate issue. Other more methodological studies have yielded indicators, tools and models for enhancing simulations at a local level, assessing risks and mapping out adaptation. Internal think-tank seminars have led to more systemic thinking on key issues relating to adaptation, such as water and soil management. Participatory approaches have been rolled out gradually to help identify solutions at a local level, co-create more resilient systems, and conduct a foresight study leading to the development of a national industry-adaptation strategy. Finally, the project also included science events open to industry stakeholders – such as trade fairs – and to the international scientific community, namely with the organization of two international conferences and the development of several European projects.

In mapping out the adaptation process, LACCAVE focused mostly on 2050, by which time the projected temperature increases would be no more than 2°C higher than the reference period (1976–2005), even though several local-level climate simulations have also been conducted for the end of the twenty-first century (Neethling, 2016; de Rességuier *et al*., 2020; Zito, 2021; Zavlyanova *et al*., 2023; Zito *et al*., 2023). It is with this timeline in mind that the project's participants worked together to create a shared vision, an analytical framework and methods that will bring about the requisite interdisciplinary approach to respond to the need for adaptation knowledge. They soon agreed that climate change is an ongoing and multidimensional process, that a great deal of uncertainty surrounds the forms it will take in the future, which vary at local level, that its impacts are global (not least on resources and ecosystems), and that adaptation must be viewed broadly, including biological processes driven by human action in a number of fields and scales (Viguié *et al*., 2014).

The LACCAVE community thus adopted a common definition of adaptation, which is regarded as all the processes and actions that a society, region or industry implements to modify its activities in response to observed or expected climate changes, thereby minimizing the negative effects of this change and maximizing its beneficial effects (Hallegate *et al*., 2011; IPCC, 2014; Caquet, 2017). As such, adaptation must be systemic and involve the analysis of impacts, vulnerability and risks on various spatial and temporal scales, by combining technical levers (Barbeau *et al*., 2014), and also giving thought to the location of vineyards, rethinking business strategies and considering the growth of the industry through its markets, institutions, regulations and the development of technical and scientific knowledge (Viguié *et al*., 2014; figure Intro-3). It was clear from the outset that there would be no single solution, such as a technological fix, and that different levers would have to be pulled together as part of strategies that could be overseen within a "sectoral system of innovation and adaptation" (Boyer and Touzard, 2021).

In general terms, LACCAVE favoured anticipation as a means of adaptation rather than reaction to the proven effects of climate change (Viguié *et al*., 2014). The project also highlighted the importance of risk perception and the conditions of acceptance of change by stakeholders in the value chain (from producer to consumer), which are crucial to getting them to commit to adaptive strategies (Teil, 2017; Neethling, 2016; Boyer and Touzard, 2021). These issues are dealt with in chapters II-1 and II-2 of this book. The scale of the changes needed for adaptation has also been considered: incremental changes, such as modifying cultivation or winemaking practices, can no doubt enhance the short-term resilience of winegrowing businesses, but implementing them one after another may not suffice and could hinder long-term adaptation (Viguié *et al*., 2014; Caquet, 2017). In the short term, there is unquestionably a need to consider no-regrets measures, namely those that are worthwhile regardless of the extent of climate change. Agroecology and agronomic practices preventing erosion fall into this category. The flexibility and reversibility of resources committed to adaptation should also be factored in, such as by diversifying grape varieties or making institutional changes, as opposed to investing in costly technological solutions that risk locking in technical systems (Viguié *et al*., 2014). Such is the importance of the long term for a perennial crop and the intensity of the climate change predicted for the second half of the twenty-first century that adaptation should be seen as a continuous, systemic and transformational process, which may involve radical changes such as a general renewal of grape varieties or a major relocation of French vineyards (Caquet, 2017; figure Intro-4). Given the intensity and speed of climate change, these potential responses should be

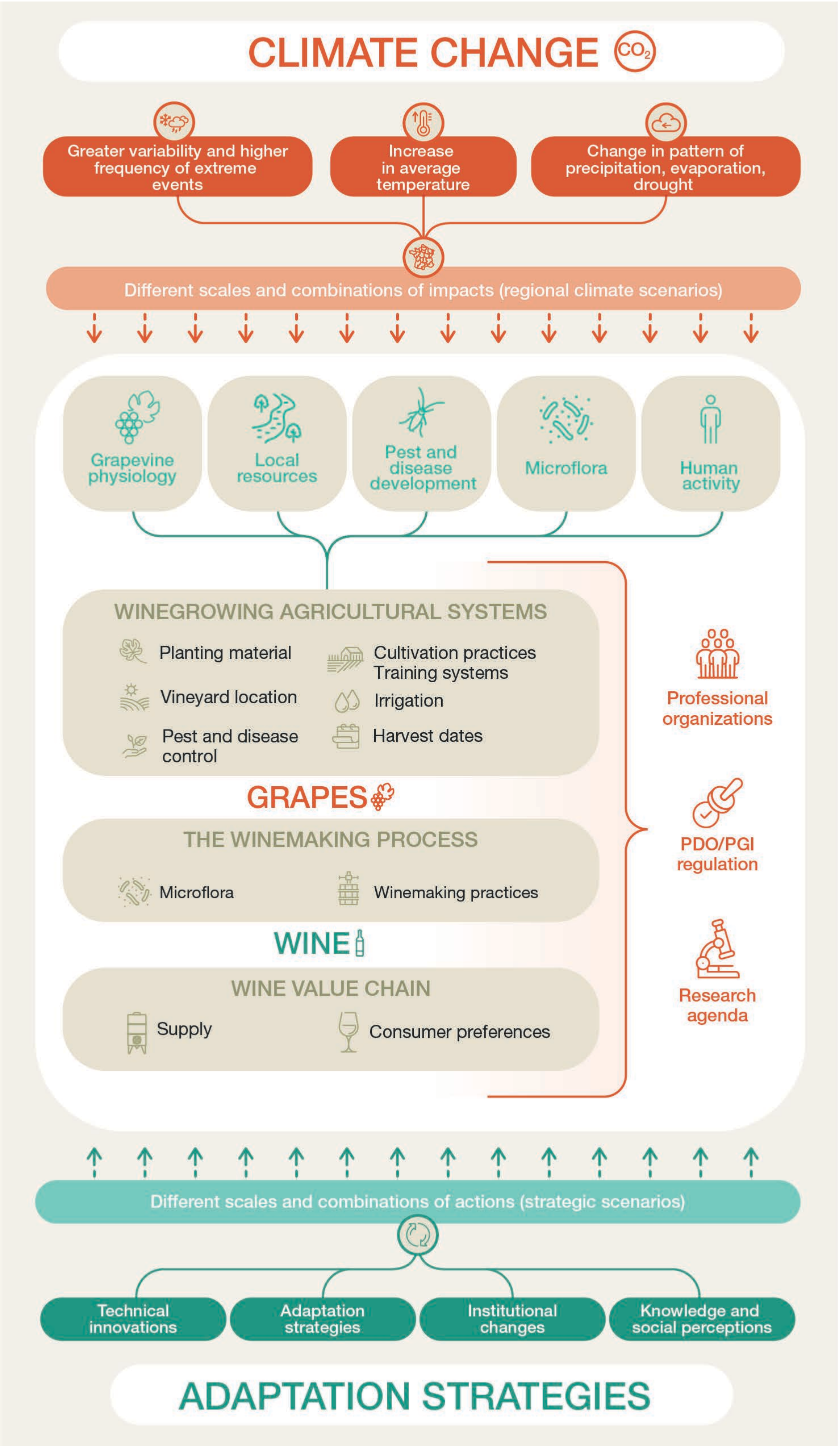

Figure Intro-3. Systemic approach to adapting to climate change in the viticulture and wine industry, according to LACCAVE. Source: Ollat and Touzard (2014).

explored and tested. As part of these processes and to encourage anticipation, it is vital that stakeholders, including scientists, interact and share experiences with each other. Participatory research is proving crucial to the production of scientific knowledge that spurs action in a context typified by urgency and uncertainty and where a host of levers need to be considered if we are to adapt. These participatory approaches were trialled on various occasions and on various scales as part of LACCAVE, and will be covered in detail in the second part of this book (chapters II-5, II-6 and II-7).

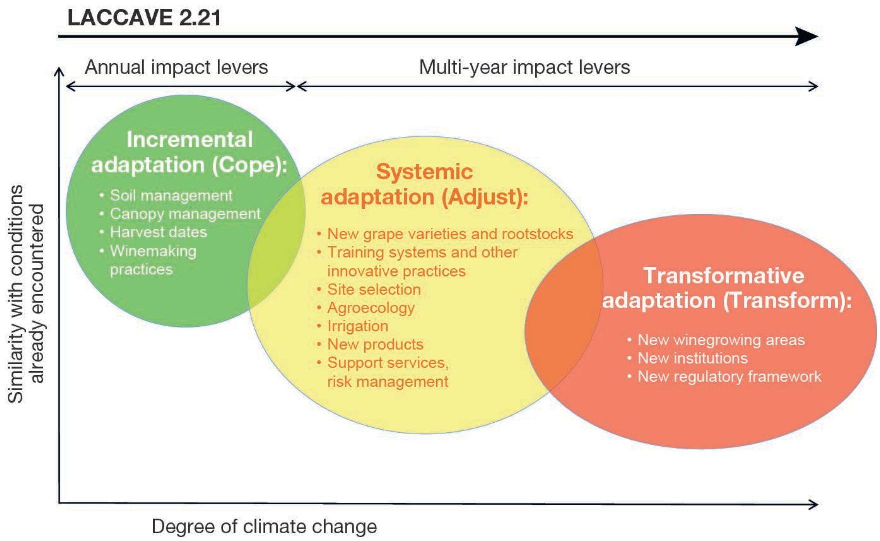

Figure Intro-4. Diagram showing adaptation processes in accordance with past experience of climate conditions and the intensity of climate change. Adapted to the viticulture system based on Thornton (2014).

This vision of adaptation formed the analytical framework of the LACCAVE project and the basis of the foresight study "The viticulture and wine industry and climate change through to 2050" (Aigrain *et al.*, 2016c), which is the subject of chapter II-7 of this book. Though a key issue, mitigation was not studied as part of the project and will not be discussed in much depth in this book. It will be covered in the conclusion as something that is likely to become a prerequisite for adaptation.

Key results of the LACCAVE project

The range of approaches implemented through the LACCAVE project yielded some key results, which are summarized below and will be expanded on in the book.

The development of shared expertise

Significant effort was made throughout the LACCAVE project to summarize the main impacts of climate change and the levers for adaptation, a process that involved leading academic and industry publications (Ollat and Touzard, 2014; Quénol, 2014; Ollat *et al.*, 2017; Ollat and Touzard, 2018; Van Leeuwen *et al.*, 2019a; Naulleau *et al.*, 2021). While these studies focus on a specific area of impact or adaptation, they generally form part of a pluridisciplinary approach that puts them into context and provides a better understanding of the contribution they can make. Pluridisciplinary contributions were made on issues vital to climate change adaptation, such as water management, biotic interactions, soils, the determination of ideotypes for grape varieties, regional approaches to viticulture, data management, the coordination of value chains, and research into the wines of the future. These adaptation-related areas of action each involve interactions between ecosystems, technical levers, socioeconomic relations and organizations, and knowledge. These areas are building blocks for more global adaptation strategies, some of which are included in the national industry strategy. Participatory seminars have been held on these themes, with presentations made available on the project website[2] and summaries that provided material for the first part of this book.

Anticipation: modelling and forecasting

Modelling is central to the sciences of anticipation and adaptation. LACCAVE contributed to the development of these approaches, making simulated agro- or ecoclimatic indicators for future climate conditions available, and to the spatial assessment of potential climate risks and opportunities for French vineyards. As well as producing purely climate-related data, the intention is also to link those data to grapevine physiological models such as phenology or, in the longer term, crop models (García de Cortázar-Atauri, 2006; Quénol *et al.*, 2017; García de Cortázar-Atauri *et al.*, 2017; Sgubin *et al.*, 2018 and 2022; de Rességuier *et al.*, 2020). Models have been used at vineyard level in the Languedoc region to help local winegrowers to create cropping systems that are resilient to climate change. These systems are tested using in silico climate simulations offering the option of dealing with water management problems and heat risks (Naulleau *et al.*, 2022a and 2022b). These approaches and the use of modelling for vineyard adaptation are described in chapters 1 and 9 of part one of the book and in chapter 6 of part two.

Foresight studies are also part of the science of anticipation. One of the key outcomes of the LACCAVE project was a foresight study conducted between 2014 and 2019 by a group of scientists in partnership with FranceAgriMer and INAO, and with the active participation of Montpellier SupAgro. As a tool for developing scientific pluridisciplinarity within the project and for spurring industry stakeholders in the main winegrowing regions into action, this foresight study helped national industry organizations draw up an adaptation strategy, which was presented to the Minister of Agriculture in 2021. This foresight study approach is presented in full in the final chapter of this book.

Participatory approaches

LACCAVE invested heavily in participatory approaches with a view to encouraging and supporting viticulture and wine industry stakeholders in the development of adaptation solutions and strategies at different scales. Aside from their contributions to the surveys detailed in chapter II-1, these stakeholders were regularly invited to take part in project seminars and discuss their expectations, the actions they were taking and their vision of adaptation (Ollat and Touzard, 2014). As part of the aforementioned foresight study (and chapter II-7), forums attended by over 500 people were held in seven regions to identify adaptation scenarios for vineyards there and to put forward solutions. The data collected were used by industry leaders to draw up the national strategy with the

2. https://laccave.hub.inrae.fr/.

support of the LACCAVE foresight study team (Ollat *et al.*, 2020). Stakeholder participation, combined with modelling and a participatory approach (which will be presented in chapter II-6), is also central to the co-creation of management systems that are resilient to climate change. Other original participatory approaches, such as viticulture Climathons, were adopted and encouraged a range of local stakeholders to come up with vineyard adaptation solutions (chapter II-5). Efforts were also made to identify existing and potential initiatives and innovations and to publicize them more widely and, if necessary, give people access to the knowledge produced and pooled in the LACCAVE network. The Vineas platform, which brings this information together, is another example of this participatory approach, albeit online (box II-5-5).

Training: front and centre in the LACCAVE project

Finally, LACCAVE was firmly committed to training. Ten doctoral candidates carried out their research as part of the project or were closely associated with it. Three of their theses dealt with the genetics and physiology of adaptation (Coupel-Ledru, 2015; Rossdeutsch, 2015; Duchêne, 2015), while five addressed local-level pluridisciplinary adaptation, often integrating modelling approaches (Neethling, 2016; Delay, 2015; Le Roux, 2017; Naulleau, 2021; Zito, 2021), and the remaining two economic issues (Boyer, 2016a; Fuentes Espinoza, 2016). Around 20 Master's students from a range of programmes also worked on the project and contributed to its success. They deserve the utmost credit for this, and they also helped to write the book's various chapters and text box features. The knowledge produced through the LACCAVE project has also been seamlessly integrated into viticulture and wine training modules. Several of these modules were entirely created by teachers involved in the project, helping to raise awareness of climate issues in university and engineering school courses. Thanks to the work carried out through the LACCAVE project, improvements have also been made to other more technical training courses for industry stakeholders, for example at the initiative of the IFV and French chambers of agriculture (box II-4-2). Examples of these courses can be found in chapter II-4.

Conclusion

Over a period of 10 years, the LACCAVE project led to the creation and organization of a network of researchers who came together to produce knowledge and tools to help the French viticulture and wine industry adapt to climate change and support industry stakeholders with their strategic thinking. Gaining a better understanding of the impacts, exploring levers for adaptation and co-creating strategies at different scales has posed challenges from a research standpoint. Yet though the scientific and political stakes have been high, these challenges have been especially stimulating. The LACCAVE scientific community rose to them by taking a pluridisciplinary approach focused on action and the dissemination of its findings across society. It learned at least as much from its interactions with industry stakeholders as from the development of more traditional scientific methods combining observation, surveys modelling and analysis. Though there is still much to be done, the primary aim of the LACCAVE project was to build up knowledge with a view to promoting adaptation actions within the industry. We can say in all modesty that it succeeded in doing that, as the 16 chapters of this book demonstrate.