Wine, climate, and institutions

- exploring the role of endogenous institutional change on climate resilience with agent-based modelling.

Matteo Bruno Ricozzi

Master's thesis • 30 hp
Swedish University of Agricultural Sciences, SLU
Faculty of Natural Resources and Agricultural Sciences/Department of Economics
Agricultural, Food and Environmental Policy Analysis (AFEPA) - Master´s Programme
Degree project/SLU, Department of Economics, 1359 • ISSN 1401-4084
Uppsala, 2021

Wine, climate, and institutions
– exploring the role of endogenous institutional change on climate resilience with agent-based modelling.

Matteo Bruno Ricozzi

Supervisor:	**Mark Brady, Swedish University of Agricultural Sciences, AgriFood Economics Centre (Lund)**
Assistant supervisor:	Maria Gerullis, University of Bonn, ILR, Chair of Economic and Agricultural Policy
Examiner:	Jens Rommel, Swedish University of Agricultural Sciences, Department of Economics

Credits:	30 hp
Level:	A2E
Course title:	Master thesis in Economics
Course code:	EX0905
Programme/education:	Agricultural, Food and Environmental Policy Analysis (AFEPA) - Master´s Programme - NM030
Course coordinating dept:	Department of Economics

Place of publication:	Uppsala, Sweden
Year of publication:	2021
Title of series:	Degree project/SLU, Department of Economics
Part number:	1359
ISSN:	1401-4084

Keywords:	adaptation, agent-based, change, climate change, cooperatives, endogenous, geographical indications, institutions, modelling, resilience, viticulture

Swedish University of Agricultural Sciences
Faculty of Natural Resources and Agricultural Sciences
Department of Economics

Publishing and archiving

Approved students' theses at SLU are published electronically. As a student, you have the copyright to your own work and need to approve the electronic publishing. If you check the box for **YES**, the full text (pdf file) and metadata will be visible and searchable online. If you check the box for **NO**, only the metadata and the abstract will be visible and searchable online. Nevertheless, when the document is uploaded it will still be archived as a digital file.

If you are more than one author you all need to agree on a decision. Read about SLU's publishing agreement here: https://www.slu.se/en/subweb/library/publish-and-analyse/register-and-publish/agreement-for-publishing/.

☒ YES, I/we hereby give permission to publish the present thesis in accordance with the SLU agreement regarding the transfer of the right to publish a work.

☐ NO, I/we do not give permission to publish the present work. The work will still be archived and its metadata and abstract will be visible and searchable.

Abstract

The literature highlights how climate change might challenge the definitions of wine geographical indications (GIs) in Europe. The central issue addressed in this thesis is whether European GI viticultural systems could tackle climate change via initiating adaptive institutional change processes to relax the constraints imposed by GI production standards. To do so, drawing from institutional economics theory and literature on cooperatives and collective brand, we developed a novel agent-based model (ABM) representing an abstract GI wine production system in the European Union (EU). Using illustrative data, our model allows testing different impact scenarios driven by climate change, spatial heterogeneity, and alternative institutional settings (i.e., voting mechanism). We used the model to explore individual and collective components of climate resilience and the relationship between economic agents and their environment. We compared the average output of 100 simulations for each of the 12 different climate-landscape-institution scenarios. The inclusion of endogenous institutional change led to considerable variations in all target variables, including the emergence of complex/chaotic behaviours. It enabled the system to reduce farm exits, increase profitability and collective brand value. We showed how landscape heterogeneity has a twofold role in the climate resilience of the system. It increases individual adaptability but obstructs collective adaptive capacity through institutional change. The two different voting mechanisms considered (i.e., relative and absolute majority) did not produce any discernible result. The study highlights the importance of policies oriented to strengthening investments in intangibles and facilitating GI rule amendments, especially in sectors where cooperatives predominate due to poor intangible investments capability and other issues connected to member heterogeneity.

Keywords: adaptation, agent-based, change, climate change, cooperatives, endogenous, geographical indications, institutions, modelling, resilience, vitivulture

Note from the author:

The use of “we” and “our” and any other similar expressions is intended for writing style purposes only. I am the sole person responsible for and author of the present thesis.

Table of contents

List of tables

List of figures

Abbreviations

ABM	Agent-based Model/Modelling
AM	Absolute Majority
EU	European Union
IAD	Institutional Analysis and Development framework
GI	Geographical Indication
GS	Growing Season
NV	No Vote
RM	Relative Majority
WTP	Willingness To Pay

1. Introduction

The European Union is the heart of global wine-grape production, hosting 45% of the world's viticultural land for a total of 3.3 million hectares (OIV 2021). In Europe, the sector is tightly linked to the concept of *terroir* (van Leeuwen & Seguin 2006). *Terroir* is the unique combination of social-environmental conditions of wine's place of origin (including soil, climate, morphology, and human factors) that interact in the co-definition of a wine's distinctive biochemical features and, ultimately, its colour, flavour, and taste.

In this context, a wine's name of origin becomes a critical price discriminant, and it is posed at the centre of marketing strategies. For this reason, in Europe, *terroir* wines are protected by Geographical Indication (GIs), which are essentially intellectual property protection tools in the form of a label. These tools are institutions that safeguard producers while setting up several constraints on production methods and quality standards (Antonelli & Vigano 2012). Producers must respect these standards or else face the withdrawal of the label.

In the last decades, climate change has had a significant impact on the sector, which will likely increase in the future. Recent reviews on climate change impacts and adaptation in viticulture can be found in van Leeuwen *et al.* (2019) and Droulia & Charalampopoulos (2021). Importantly for our analysis, climate change is likely to mutate traditional wine features all over Europe (better or worse). Micro-climatic conditions are fundamental in defining wine quality, and GI recognition depends not only on keeping high-quality standards but also specific distinguishable organoleptic features. Therefore, if climate changes, other factors must adjust accordingly, such as location, varietal selection, viticultural and oenological practices.

European GI wine systems are rural territories with a long viticultural tradition, a production structure led by small family businesses and cooperatives (Castriota 2020 p. 60). Collective decision-making is an essential aspect in these systems, given the prevalence of cooperatives and other collective agents such as consortia of producers, controlling general marketing of the GI, assuring quality, and maintaining production standards (Gori & Alampi Sottini 2014). Moreover, the small average farm size and limited individual resources heighten the dependence on collective reputation and territorial brands (i.e., GIs such as Chianti, Burgundy, or Pfalz).

Literature on cooperatives highlights their many weaknesses especially related to the imperfect definition of property rights (Chaddad & Cook 2004) and different forms of heterogeneity within them, including members' socio-economic and product heterogeneity (Höhler & Kühl 2017). The result is the increasing diversification of members interests and poor coordination incentives, which might slow down collective decision-making and fuel opportunistic behaviours (e.g., free riding).

Maintaining high-quality standards and creating efficient quality assurance mechanisms is the basis for protecting the collective value of the GI, which ensures higher returns for all producers and can foster cooperation and environmental stewardship (Belletti *et al.* 2017). On the other hand, GI standards and constraints might limit farmers' adaptability to climatic challenges, possibly exacerbating clashes in collective decision-making (Clark & Kerr 2017).

Nonetheless, managing a GI is a grassroots process, and amendments to production rules are allowed. However, it requires cooperation at the local scale and might generate complex interactions between individual and collective agents with the potential emergence of social dilemmas. For example, low-quality farms would be willing to lower the quality standard to maintain the GI label at the expense of the quality reputation built by others. Therefore, if local stakeholders can activate institutional adaptive and transformative processes (i.e., through rule emendation), it remains unclear whether the present nature of local institutions and the cooperative structure amongst agents can assure that these processes will take place to safeguard the value and resilience of the system.

In our analysis, we refer to the definition of "specified resilience", which is: "The resilience of what, to what" (Folke *et al.* 2010), to describe the capacity of the system under scrutiny to endure climate change disruptive processes and maintain its functions, focusing on profitability, preventing farm exits, and landscape issues.

Parallel to socio-economic factors, spatial and environmental heterogeneity could also curb cooperation through widening the range of climate change impacts. Farmers in low areas could be the biggest losers, being the first affected by rising temperatures. At the same time, producers in higher areas could suffer less or even be better off. In general, diversity is associated with resilience, and single farm adaptability might benefit from landscape heterogeneity. However, the diversified nature of microclimatic impacts could act as a destabilising factor for collectives and hinder cooperation.

In a nutshell, due to the primacy of small farms with limited individual resources, and the constraining nature of GI rules limiting several climate adaptation practices, it is reasonable to assume that institutional change (i.e., changing of common production rule/standards), will play a key role in climate adaptation for European viticulture. Moreover, the cooperative structure of these systems questions their resilience further. Institutional change as the outcome of the collective decision-making of a large number of small heterogeneous farms might be unpredictable and chaotic. On the other hand, the possibly ambiguous effect of spatial and environmental heterogeneity on climate resilience increases the system's complexity.

If successful, institutional change could be one of the few mechanisms available to prevent farms from losing higher premia associated with the GI label and exiting the business. Moreover, it could strengthen collectives, such as cooperatives and consortia, and avoid the decline of the collective brand value.

Agent-based modelling (ABM) is a methodology particularly suitable to explore the issue just described. First, it allows studying the emergence of complex phenomena driven by the interaction of autonomous agents and their environment. Therefore, with limited assumptions on the system's underlying principles, and only a few simple rules at the individual level, we can explore how multiple agents and spatially explicit environmental variables contribute to its definition in a bottom-up approach. Second, exploring the impact of possible future climate change scenarios in a spatially explicit environment is a well-suited task for a dynamic tool such as ABM. Third, when studying institutions and individual behaviour in situations where rules are the object of choice (i.e., endogenous institutional change), the level of complexity is too high to rely on game-theoretical approaches or field experiments (Ostrom 2009 p. 24). With ABM, we can simulate a perfectly controlled experimental setting, with numerous interacting automated agents, to test the effect of exogenous factors on collective action (Poteete *et al.* 2010 pp. 287–290).

Employing ABM in the analysis of cooperation, collective behaviour, and institutional change in agricultural systems is a relevant and still unexplored track, at least in Europe (Huber *et al.* 2018).

The central issue addressed in this thesis is whether European GI viticultural systems could tackle climate change via initiating adaptive institutional change processes to relax the constraints imposed by GI production standards. In order to do so, we developed a novel agent-based model (ABM) representing an abstract GI wine production system in the EU. The novelty of the model stems from farms' ability to engage in endogenous institutional change to amend a quality standard.

Thus, the main research question of the present study is:

How do different institutional (i.e., voting mechanisms) and environmental (i.e., spatial heterogeneity) settings influence the climate resilience of wine GI production systems?

The work is not based on hypotheses testing but is exploratory in nature. Using illustrative data, our model allows testing different impact scenarios driven by climate change, spatial heterogeneity, and alternative voting mechanisms. The model allows the consideration of both individual and collective/institutional components of climate resilience and the relationship between economic agents and their environment.

The thesis unfolds as follows: in the next section, we present a brief literature review focusing on the gap addressed in this research. The most important theoretical aspects inspiring the model are covered in section three, with due attention to institutions and institutional change. Section four gives a brief description of the model following the "Overview, Design concept, Details + Decision-making" (ODD+D) protocol[1] (Müller *et al.* 2013). Moreover, we complete this methodological section by addressing the experimental design used to run the simulations. Section five presents and discusses the most relevant findings before we draw conclusive remarks in section six.

[1] The full version of the ODD+D protocol can be found in appendix 1.A.

2. Literature Review

Climate impact studies on viticulture constitute a well-established research field. Climate change affects viticulture by increasing average growing-season temperatures, altering rainfall regimes, and intensifying weather variability. Several papers focus on macro-level issues (Mozell & Thach 2014; Wolkovich *et al.* 2018), while others on assessing local socio-economic effects and exploring climate change adaptation policies with the use of modelling (Bernetti *et al.* 2012; Zhu *et al.* 2016; Sacchelli *et al.* 2017), including ABM (Delay *et al.* 2015; Tissot *et al.* 2017). It is beyond the scope of the thesis to address this field in more detail. Instead, given their relevance for the sector, we focus on reviewing the literature on cooperatives, highlighting vulnerabilities typical of this organisational structure for adapting to challenges. Collective agents such as cooperatives and producers' consortia are essential components of the sector, particularly regarding collective brands such as GIs. Finally, we move on to how climate change challenges GIs and the role of collective decision making and institutional change as an adaptation measure.

In Europe, particular socio-economic and organisational features may pose additional climate adaptation challenges to the wine sector. First, the sector is dominated by small farms, and cooperatives take a significant market share (Castriota 2020 p. 60), estimated at around 42% (Bijman *et al.* 2012). Second, it is highly dependent on the concept of *terroir*, collective brands and GIs, which might be threatened by climate change.

Cooperatives are democratic, non-profit, member-based organisations driven by use (Bijman *et al.* 2014), meaning that their first objective is to support members'/users' incomes. Cooperatives are owned and democratically controlled by their members (i.e., one member – one vote). At the same time, profits are redistributed based on use/patronage (i.e., the share of deliveries to the cooperative) (Chaddad & Cook 2004). In the classic case, members constitute the general assembly that elects the board of directors and supervisory board, respectively the administrative and control bodies. The board of directors has direct managerial power and is monitored by the supervisory board, which reports directly to the general assembly. The general assembly has ex-post control on the decision-making process, even though control can be enhanced by approving special cooperative bylaws. Moreover, the general assembly preserves the rights to make critical decisions such as terminations, mergers, by-law amendments, etc. (Bijman *et al.* 2014). Parallel to the tight members' control, cooperatives exhibit two core weaknesses: first, the one described as ill-defined property rights, and second, they present a high level of heterogeneity within members. Property rights are restricted to members, non-transferable, non-appreciable and redeemable (Valette *et al.* 2018). This ownership and governance structure incentivises free-riding and creates two other typical issues in cooperatives, denoted as the horizon and portfolio problems. As a result, coops suffer from reduced coordination incentives and low capability to attract investments from members (Chaddad & Cook 2004). Furthermore, these issues are exacerbated by the heterogeneity of farm size and geo/spatial conditions, members' socio-demographic features, and product characteristics, as outlined by Höhler & Kühl (2017). Even though causality might be ambiguous, the authors describe how heterogeneity at multiple levels translates to poor coordination of members' interests, leading to high collective decision-making costs, poor performances, dissatisfaction, and lack of commitment.

To tackle these institutional challenges, modifications to the traditional cooperative model have emerged concerning the ownership structure (Chaddad & Cook 2004) and internal governance (Bijman *et al.* 2014). However, the traditional model is still the most common in the EU (Bijman *et al.* 2014).

In wine cooperatives, members are small winegrowers delivering grapes to the cooperative firm that owns production means and controls the wine-making process. In this integrated production framework, delivered grapes are usually pooled, and the cooperative has limited control over quality (Santos-Arteaga & Schamel 2018). Consequently, delivery-based benefit distribution and the decentralised wine-making process result in overproduction incentives and quality free-riding (Schamel 2015).

Nonetheless, wine cooperatives have long survived alongside corporations. Santos-Arteaga & Schamel (2018) demonstrate how they might achieve higher social surpluses when homogeneity of interests between ownership and management units exists. Moreover, despite the lower efficiency, wine cooperatives have also proven to be more resilient than corporations. Valette *et al.* (2018) show how cooperatives survival rates outclass those of corporations due to their ability to distribute the impact of crises among their members. Since they aim at maximising members' income, profits are directed to members' remuneration. Therefore, lower turnovers are directly reflected in lower remunerations, and the cooperative can survive at the expense of its members. The authors also point out that the opposite applies in times of prosperity, and the practice of redeeming equity to its members reduces the coop's investment capacity. This contradiction makes cooperatives resilient even though they are generally short-sighted in terms of their business horizon (i.e., maximising members' income potential).

The low investment capability of cooperatives is also reflected in their insufficient expenditure in intangibles, primarily related to branding and product diversification. Substantial intangible investments are associated with high profitability and low risk (Amadieu & Viviani 2011), and wine cooperatives miss the opportunity of increasing economic performance and benefits from export (Amadieu *et al.* 2013). Even if Europe's largest cooperatives aim at product differentiation and marketing branded wine, only a minor share succeed, while the majority sells bulk wine (Storchmann 2018). The Common Agricultural Policy incentivises cooperatives to invest in value-enhancing activities (e.g., marketing, quality assurance, and product differentiation). Nevertheless, cooperatives are still far behind corporations; one reason why they suffer from reputational discounts (i.e., lower prices for comparable quality) and are widely stuck in the low-quality segment (Schamel 2015).

In the EU context, cooperatives are not the only collective agents in the wine sector. Producers might also join forces in a consortium to strengthen their collective reputation and create a collective brand. Examples of these organisations are the "*interprofessions*" in France and "*consorzi di tutela*" in Italy. Usually, they comprise the GI spatial domain and represent all producers using the collective brand (including cooperatives and private firms). These consortia assure producers respect the standards defined by the GI and invest in marketing and general regional branding (Gori & Alampi Sottini 2014).

Small private businesses and cooperatives benefit from GI and other forms of collective brands due to the limited marketing effort and other internal problems afflicting cooperatives (e.g., quality free-riding). Reputation is essential in the wine sector since it deals with an experience good, and consumers' willingness to pay (WTP) is based on their quality expectations. Castriota (2020 chap. 6) outlines clearly the role of reputation distinguishing three kinds: institutional reputation (i.e., merely having a GI label), collective reputation (e.g., the name of a specific GI/territory, subarea or producers' collective), and individual reputation (i.e., firm-specific based on a private brand).

Several empirical studies focused on the effect of different forms of reputation on wine price, using quality signals of wine guides ratings. Schamel (2009) compares the effect of wine ratings on wine prices in several regions in the world, controlling both for the effect of collective reputation (i.e., the average of past quality in a specific region) and the effect of individual reputation (i.e. if the firm was above or below the regional quality). He shows that in most cases, below-average firms benefit from regional reputational spillovers, increasing their premia, while the high-quality firms rely less on the regional brand. Quality is important, but it is not the only element affecting consumers' WTP. Beckert *et al.* (2017) demonstrate how other symbolic characteristics of wine can explain wine price differences (e.g., artistic components, *terroir*, regional history). Such characteristics build up the symbolic capital of a region and can be communicated to the public by investing in marketing and advertising. See Sellers-Rubio *et al.* (2018, 2021) for an overview of advertising and collective wine brands. Finally, belonging to a GI can increase WTP for experience goods in other ways. In a theoretical model, Fishman *et al.* (2018) show that a high number of producers in a collective brand increases consumers' WTP since they have more information (reducing uncertainty) about past quality than private brands. However, this happens only in strict quality control settings, whereas a rising number of producers increase the risk of collective brand failure.

In short, the predominance of small firms and cooperatives with a low capacity of investing in private brands makes them highly reliant on collective brands for institutional reputation. Also, the weak definition of property rights and heterogeneity within cooperatives intensify free-riding incentives and the conflict among members' interests, making it even harder for a coop to establish a solid collective reputation and enjoy higher profitability. Finally, the presence of other collective agents such as GI consortia increases the complexity of the governance structure, raising questions on the effectiveness of the collective management of these brands.

Therefore, we come to the second potential vulnerability of European viticultural systems to climate change: the dependence on collective brands and the GI institutional system. Climate change threatens the concept of *terroir* and the effectiveness of GI institutions by changing traditional wine features. If quality changes, other factors must adapt accordingly to keep using the GI label, such as location, viticultural and oenological practices, or vine variety. GI regulations often obstruct these adaptation strategies.

Clark & Kerr (2017) directly address the climate vulnerability of wine GIs, focusing on the fussy definition of local climatic attributes, quality features and production standards. Moreover, they argue that adaptability is threatened by climate impacts heterogeneity at the local scale, possibly obstructing cooperation and sustainable innovation. However, at least in other sectors, GIs have proven to be distinctly malleable. Amendments to the production standards are possible and frequently initiated by local agents. Thus, GIs should perhaps be "*conceptualised as evolving institutions and not as static protected food production systems*", as Quiñones Ruiz *et al.* (2018) contend. The question now is whether it is possible to describe successful (or unsuccessful) amendment processes and the underlying socio-economic, ecological and institutional drivers. Both system-internal (e.g., local-knowledge formation and negotiation processes) and system-external forces (e.g., market forces and new varieties) might prompt institutional change in the GI sector (Edelmann *et al.* 2020).

However, there is a lack of institutional change studies on GI wine systems, and more generally, of evidence connecting different systemic features to its adaptability (e.g., the incidence of cooperatives and corporations; the governance structure, including collective decision-making; environmental and socio-economic heterogeneity). Moreover, to the author's knowledge, the role of institutional change in sectoral climate adaptation is yet to be explored.

In summary, given the dependence on collective GI brands, the ability of local systems to adapt to external climatic challenges via a process of endogenous institutional change (i.e., GI rule change) is a prerequisite to maintain high quality and reputation when faced with the challenge of climate change. The adaptive nature of GI rules allows farmers to propose amendments to mutate production standards and make GI rules more flexible. However, the presence of several collective agents and many heterogeneous individuals does not guarantee the success of these processes. Cooperation and collective action are fundamental research topics to explore the resilience of agricultural systems, likely even more for those based on collective and institutional reputation such as wine GI systems.

This research project seeks collocation in this research gap, addressing the role of endogenous institutional change on climate resilience in a collective group of farms acting as a cooperative. We do so by developing a novel agent-based model to study the impact of social, institutional, and environmental conditions on the system's overall functions. Employing ABMs in the analysis of cooperation, collective behaviour, and endogenous institutional change in agricultural systems is a relevant and mostly unexplored topic in the field (Huber *et al.* 2018). Therefore, this research is also a contribution to this field. The following section underlines the central theoretical components inspiring and guiding the present study. We focus on the definition of institutions and institutional change, and we briefly go over the concept of resilience and the fundamental principles guiding agent-based modelling.

3. Theoretical Grounding

3.1. Institutions and Endogenous Institutional Change

In the previous sections, we often referred to institutions, rules, and institutional change. In the following research, we adopt the institutional perspective provided by the work of Elinor Ostrom, with particular attention to her book "Understanding Institutional Diversity" (Ostrom 2009). The book provides detailed definitions of institutions and formalises a universal framework to analyse institutional diversity denoted as Institutional Analysis and Development (IAD) framework. Notably, this research draws on Ostrom's vertical classification of institutional arenas, enabling the analysis of institutional change at multiple levels, her attention to the role of institutions in safeguarding the commons (e.g., such as GI's collective brand value), and the interaction between institutions, agents and the environment (e.g., climate change impacts). Moreover, it benefits from its examples of different experimental settings to study institutions and institutional change, including ABMs.

Following the IAD framework, individual agents make decisions in an action situation defined by exogenous institutional, socio-economic (i.e., attributes of the community) and environmental conditions. Individual actions produce personal and collective effects, and social dilemmas can emerge in the presence of competing outcomes. More specifically, this applies to *operational* action situations, i.e., those producing direct impacts on individuals and their environment. Other types of action situations exist and are vertically integrated, each one producing rules/institutional constraints for the one below.

Institutions have the critical role of reshaping agents' incentives and harmonising individual and collective outcomes. Social norms and rules are both institutional statements; they alter individual expected outcomes, influencing their decisions and the system's overall efficiency.

The ADICO syntax can be used to classify different institutional statements. The main difference between norms and rules stems from the or else definition and the presence of control and punishing authorities (Crawford & Ostrom 1995). Rules can be classified horizontally based on their aim (i.e., the object of regulation, such as action and outcome rules) and vertically based on the level of an action situation under analysis. Ostrom distinguishes several nested action situations. The operational situation is the one in which agents' behaviour directly affects real-world state variables. For example, in our analysis, a group of farmers deciding how much to invest in quality before delivering to the cooperative, affecting the final wine quality and collective reputation of the system. One level above, the "collective-choice" situation, is where a group of individuals act in crafting and changing rules (i.e., institutional change) that will affect the operational setting. For example, the same winegrowers collectively engaging in setting rules for the management of the commons and defining control and punishment mechanisms. Ostrom also describes higher levels of "constitutional" and "metaconstitutional" situations, which are not considered here, even though they are relevant for, say, climate change adaptation strategies at the regional or national level.

Institutions change due to several causes. Ostrom (2009) identifies depletion of resources over time as a primary source of (endogenous) institutional change, which instigates the individual to calculate the expected cost and benefit from a change in their access to resources. The argument is that when the resources are found in large quantities or the economic value of resources is high; actors face low individual incentives to create rules to manage the resources. Endogenous changes can make the institutions more or less sensitive to environmental changes and play a significant role in defining a system's resilience.

In our study, winegrowers in a GI region benefit from particular microclimatic conditions, granting high wine quality and set quality standards that increase their reputation. However, when the climate suitability of the region decreases, standards are also questioned, urging for institutional change.

3.2. Agent-Based models

When studying institutions and individual behaviour in situations where rules are the object of choice (i.e., endogenous institutional change), the level of complexity is often too high to rely on game theory and field experiment (Ostrom 2009 p. 24) ABMs can provide an effective tool to study complex social-ecological and institutional interactions and the emergence of non-linear outcomes (Schulze *et al.* 2017). In Poteete *et al.* (2010 p. 272)**,** an ABM is described as a "computational representation" of autonomous agents interacting with each other on a limited level (i.e., micro-level), leading to patterns on a macro level. By explicitly defining a few agents' decision-making rules and identifying the conditions in which interaction/cooperation may develop, we can test theoretical assumptions and study the emergence of aggregated outcomes in collective decision-making contexts. Moreover, ABMs can explicitly include agents' heterogeneity at multiple levels, including state variables, cognitive capacities, preferences, and decision-making rules. Agents can derive information from the environment and perceive the state of their shared common resource. Based on their objectives/goals and attributes, agents decide on their actions affecting the environment and other agents (Poteete *et al.* 2010 p. 288).

Due to its flexibility, the ability to consider space and agents heterogeneity explicitly, ABM is particularly suitable to explore theoretical questions related to social-ecological systems, including agricultural ones. In these systems, humans, institutions, natural agents, and other abiotic environmental processes are connected in complex feedback loops. Schulze *et al.* (2017) offer a review of achievements, issues, and future challenges for ABM applications on social-ecological systems. Even if ABMs were initially used as theoretical and explorative tools, empirical applications aiming to produce policy recommendations have risen in the last years. However, much work is needed to include the role of institutions, hierarchical interactions and multi-level decision-making (Schulze *et al.* 2017).

If ABMs allow capturing the complexity inherent in agricultural production systems, it can become extremely complicated to calibrate model parameters or set up agents decision-making rules. Sun *et al.* (2016) highlight the difference between complexity (referring to model output) and complicatedness (reflecting a model's construction) of ABMs. While complexity should be high to study complex systems' dynamics, complicatedness must be just enough to fulfil the modelling purpose (e.g., theoretical vs empirical) and answer a relevant research question. Over a specific limit, increasing model complicatedness does not increase its explanatory power while carrying several disadvantages in terms of results' interpretation, and model clarity and usability.

An insightful comparison between theoretical and empirical ABMs is given in Taghikhah *et al.* (2021). Empirical models, in which theoretical assumptions are relaxed by the empirical calibration of models' parameters, have a greater capacity for explaining site-specific dynamics. On the other hand, theoretical models, based on secondary data and the application of theoretical rules, can perform almost as well as the empirical counterpart in the study region while conserving higher adaptability to different contexts.

Few ABMs implement endogenous institutional change, while in Europe's agricultural economics landscape, there seems to be no example of such (Huber *et al.* 2018). Smajgl *et al.* (2008) present a conceptual framework enabling agents to develop new actions, including the proposition of new rules. Essential in this process is to enable agents to infer relationships between different environmental conditions, individual actions, and outcomes. Finally, capturing externalities caused by other individuals is another crucial aspect to consider when modelling endogenous institutional change.

In our model, we look at institutional change as the endogenous grassroots rule changing process. Given what has been said on institutions, the process is guided by changes in single agents' perceptions of their environment and exogenous collective-choice rules (i.e., voting mechanisms), defining the framework in which agents can change operational rules. Farm agents act in both operational (viticultural-wine making activities) and collective-choice situations. In the latter, they vote to change the "aim" of a GI quality standard, which can be defined as an outcome operational rule in Ostrom's terms.

3.3. Climate Resilience

In the analysis of climatic impacts and farms' adaptation processes in the operational and collective-choice situations, we often refer to the concept of resilience. We adopt the definition given by the literature on adaptive cycles and social-ecological systems. Resilience is the capacity of a system to endure disruptions, maintain its functions and equilibrium state. This goes beyond the idea of mere conservation of the original system equilibrium and embraces three major components: robustness, adaptability, and transformability (Folke *et al.* 2010).

Due to the constrained scope of a master's thesis, we focus on the definition of "specified resilience", which is: "The resilience of what, to what" (Folke *et al.* 2010). Indeed, the main goal is to build a model with the potential of assessing the resilience of a typical European viticultural system to the specific challenge of climate change and how endogenous institutional change might affect it.

The framework proposed by Meuwissen *et al.* (2019) to assess specified and general resilience at the farming system scale is strictly applicable to viticulture. As primary functions, GI wine systems provide private (e.g., wine, income) and public goods (e.g., environmental and landscape quality and the GI brand as a regional development resource). Hence, we will try to explore climate resilience through the provision of these functions.

Finally, in the attempt to apply resilience thinking to this study, we bring in evidence from several disciplines (i.e., economics, sociology, agricultural sciences, law and climatology) both in model development as well as in the results and discussion phases which are at the core of the following chapters.

4. Methods

In the previous sections, we highlighted how climate change might challenge the definitions of collective regional brands such as GIs. At the micro-level, climate change is likely to affect farmers' ability to respect the quality standards by altering traditional wine features. Parallel to quality targets, producers must also employ traditional production methods, limiting "technological adaptation". In this setting, we discussed how institutional change, through the collective action of local producers in the amendment of production standards, might be a secondary adaptation branch worth investigating. However, it is unclear how local institutional, socio-economic, and environmental factors influence this "institutional adaptation" process.

European viticulture is particularly vulnerable to potential climate effects on GI. Small farms have little capacity to predict climatic impacts and select effective adaptation practices. Furthermore, several wine-making territories in Europe are controlled by cooperatives that rely on GI collective brands due to low investing capacity in intangibles and private brands. Above cooperatives, consortia of producers are another important collective agent in the sector that manage the GI and can include cooperatives and corporate firms in a GI area. The predominance of these collective agents implies a complex collective decision-making framework, where ill-defined property rights and members' heterogeneity might lead to the emergence of social dilemmas and slow down the institutional change process.

We represent this framework in an ABM with endogenous institutional change, allowing us to study how environmental and institutional settings might influence the system's adaptive capacity and climate resilience. In the model, we assume that a single cooperative coordinates a group of small farms in a recognised GI region. In this way, the cooperative is also the only agent managing the GI and responsible for any change in the production standards. Therefore, we merged the two stages of collective decision making: first between the cooperative's members and second between GI producers in the region. The new collective agents, representing both cooperative's and GI consortium's management board, will be called "GI board". Furthermore, modelling a single cooperative, we can ignore farms' ability to invest in their own brands and the trade-off between collective and private brands. Second, drawing from traditional cooperatives' governance structure, we can approximate the endogenous rule changing process to a one-member-one-vote collective decision. In the next sections, we present the model's essential components. Then, we go through the experimental design driving the model's simulations.

4.1. The model

We used the "*Overview, Design concept, Details + Decision-making*" (ODD+D) protocol (Müller *et al.* 2013) first as a model development guide and later to provide comprehensive and standardised model documentation. A full version of the protocol is provided in appendix 1.A of the thesis.

4.1.1. Overview

The model aims to test how different collective-choice rules (i.e., voting mechanisms) and spatial heterogeneity affect the interaction among wine GI stakeholders through an endogenous institutional change process. The outcome of this process could affect the system's climate resilience. In the model, farm agents can endogenously change one common operational rule through voting, precisely, a quality standard. The model allows testing different impact scenarios driven by two exogenous climate change processes and different institutional and environmental settings. As a theoretical model, it can be used to explore general system dynamics employing illustrative data representative of an average GI wine production system in the EU. Therefore, the aim is not to describe or predict any real-life setting. However, it might provide interesting theoretical insights on the role of institutional change in climate adaptation and resilience of agricultural production systems, particularly as a starting point for future research and model development. The model was programmed in NetLogo® (Wilensky & Evanston 1999) v 6.2. The R (Thiele & Grimm 2010) and GIS extensions were used in the initialisation. The code and all model materials are available on the author's GitHub page[2].

4.1.2. Entities and agents

The model explicitly considers the spatial dimension in a 100x100 regular square lattice. Each cell corresponds to one hectare defining a total region of 10 km^2. Patches have different state variables, including soil quality, altitude, and microclimate. The model is dynamic, running through 55-year simulations in one-year timesteps. Two agent types are involved: farms, embodying individual human

[2] https://github.com/mbricozzi/thesisModelABM

agents, and the GI board representing an institutional/collective agent. The farms' main state variables are their location and land endowment, a capital stock variable, a list of past vintage quality and profits that function as a memory base in decision-making. Moreover, farms also have a “ballot” variable which they use in the institutional change process. On the other hand, the GI board has only one variable (revenue) to collect fees from farms each year.

4.1.3. Model dynamics

Figure 1 summarises the main model components and overviews the scheduling from point 1 (environmental change) to point 10 (institutional change process). Every simulation starts with an exogenous regional warming trend updating each cell’s microclimate and potential wine quality. Farms and the GI board can sense environmental variables such as slope and wine quality and use them to make decisions. Farms have partial sensing capacity (i.e., limited to their neighbourhood), while the GI board has global sensing capacity, and information is free to retrieve.

Then, the model’s schedule is conceptually divided into two action situations. Every year, in the operational situation, farms follow simple heuristics to maximise profit and maintain high average quality levels by adapting to climate change. Farms can act on land use decisions only. They face two different prices depending on whether their average quality is higher or lower than the quality standard. First, farms can set unprofitable plots fallow. Second, after selling the wine, based on the memory of past quality, they try to substitute low-quality plots with high-quality ones in their neighbouring patches. Finally, they can also abandon plots if they are no longer profitable. Importantly, no land market is implemented (see sub-model “farm heuristic”). Moreover, it is assumed that farms always respect the quality standard, for example, implying that the GI Board acts effectively in creating incentives to follow the rules (i.e., no moral hazard considered).

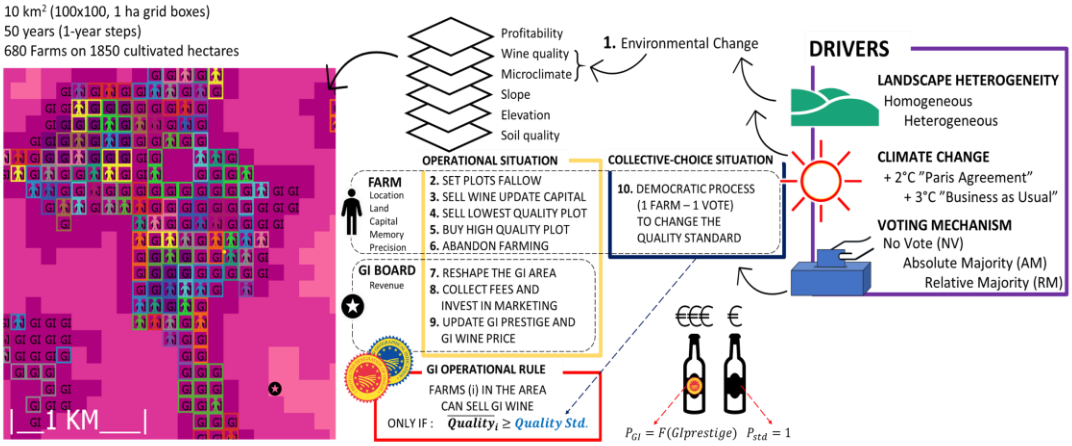


Figure 1. Model overview and schedule.

The GI board acts after farms in the operational situation. First, it updates the GI area attributing the label only to patches with wine quality higher than the quality standard. Second, it collects a fixed percentage of the total revenue and spends it on marketing to increase the collective brand's value. The rest of the budget is assumed to be allocated in quality control, ensuring farms respect the standards and for other administrative expenses. The brand value increases the prestige of the GI and partially substitutes for quality, which ultimately affects GI wine price. So, the last action of the GI board is to update the GI prestige and GI wine price. Thus, this agent does not make decisions but applies a fixed rule and updates global variables such as collective brand value, GI wine price, and GI area. (More on the mechanism driving GI prestige and wine prices in section 4.1.5).

In the end, the collective-choice situation arises when the GI board has concluded its actions and involves only farm agents. A democratic process is initiated every five years in which each farm can cast one vote to change one GI operational rule (i.e., the quality standard). They vote based on the memory of past vintage quality. Ballots are collected, and the quality standard is changed depending on the voting mechanism in place (See Appendix 1.D for a general flowchart of the model).

4.1.4. Initialisation

First, elevation is defined randomly from a uniform distribution (ranging from 0 to 800 m). A random raster is generated and then smoothed with a gaussian kernel using an R program. The same technique is applied to generate a raster for soil quality. These rasters are used in the NetLogo programme to define the spatial environment. Slope data is calculated by performing a convolution of the elevation data frame with the GIS extensions.

The elevation is used to downscale an arbitrary given regional average growing season (GS) temperature (17°C). We want to model the case in which the region has already reached its climatic optimality for the vine variety in use. Therefore, we set an optimal GS temperature matching the average GS temperature of 17°C (more information in appendix 1.B). Average GS temperature and soil quality are then used to define the potential wine quality for each plot "i" using equation 1 (soil and wine quality range from 0 to 1)

$$\mathrm{WineQ_i} = 0.4 \times \mathrm{SoilQ_i} + 0.6 \times \left(1 - \frac{(\mathrm{optGStemp} - \mathrm{GStemp_i})^2}{\mathrm{optGStemp}}\right) \quad (1)$$

We combined Eurostat[3] country-specific data on total farms and cultivated hectares for PDOs (the most restrictive GI label) with data on the total number of PDOs

[3] Eurostat wine statistics

found in the GI database of the European Commission "eAmbrosia"[4]. Only the top five wine producers (France, Spain, Italy, Portugal, and Germany) were considered. With this data, we calibrated a representative GI region consisting of 680 farms over a total cultivated area of 1850 ha, with an average farm size of 2.72 ha. Then, the quality standard is set as the minimum average wine quality of farms (i.e., they can all respect the standard in time zero). The total cost per hectare is given by equation 2, where FC = 2500€ is the fixed costs for keeping any plot productive (including fallow plots or with juvenile vines). Variable costs apply to productive plots only and are related to labour costs and slope as in Delay *et al.* (2015). Given the yearly salary of 20000€, a worker can harvest 10 ha with an average slope ≤ 10% (slope = [0, 1]). Thereafter harvesting becomes increasingly difficult with slope. In this way, we skip modelling hiring labour and use a continuous labour cost variable per hectare (e.g., a plot with a slope of 25% requires 0.25 farmers, thus 5000 €/ha*yr).

$$\mathrm{TC_i} = FC + \mathrm{slope_i} \times 20000 \qquad (2)$$

$$\mathrm{prof_i} = 5000 \times \mathrm{p_w} - TC_i \qquad (3)$$

Wine yield is fixed at 5000 l/ha, and two prices are given at the start: standard wine is sold at 1€/l and GI wine at 1.5€/l. Equation 3 is a patch-specific profitability variable considering total costs and total revenues. Finally, the land price is proportional to quality and is calculated following equation 4, with "giLabel" being a dummy variable. Official data on viticultural land prices is hard to find. In France, average prices, excluding the Champagne GI, were estimated at around 69000 €/ha in 2017[5]. Here we ponder a maximum price of 70000 €/ha.

$$P_i^{land} = \mathrm{wineQ_i} \times 50000 + \mathrm{giLabel_i} \times 20000 \qquad (4)$$

4.1.5. Sub-models

Environmental change

A linear and deterministic climate change process raises the average GS temperature of each plot every year. Assuming to start around 2020, two climate change scenarios are considered, corresponding to a +2°C and +3°C temperature increase from pre-industrial age to 2100, with a yearly increase of 0.0125 and 0.025 °C, respectively (see appendix 1.B).

---

[4] eAmbrosia data base

[5] See this report from BNP Paribas: https://wealthmanagement.bnpparibas/en/expert-voices/agrifrance-2019-wine-growing-land.html

Farm heuristic

Leave plot fallow ("profit maximising" heuristic)

First, farms calculate the average wine quality of their productive plots. They adopt two different "strategies". If the average quality is greater than or equal to the quality standard, they can pool and sell all wine at the higher GI premium. Otherwise, they can split production and sell both GI and standard wine separately. Leaving a plot fallow is the only way farms can avoid paying its variable production costs, and they do so if a plot's expected profit is less than - 2500€ (i.e., fixed costs of keeping plot fallow).

Sell wine and update capital

Farms collect their harvest, sell the wine to the respective prices, and update their capital. They have no access to credit and exit the business if production costs cannot be covered. In a cooperative, revenues would be redistributed based on patronage; thus, we simplify further and assume that each farm directly sells wine, omitting the delivery to the GI board. There is no real market for wine, and production disappears at given prices.

Sell plot lowest quality plot

As a long-term adaptation measure, farms can buy a new high-quality plot each year. This strategy is applied when farms perceive their average quality has decreased over the previous five years (farm's memory). New vineyards' installations are strongly regulated in the EU and can reach a maximum of 1% of the total planted area each year (Pomarici & Sardone 2020). To avoid dealing with a planting rights market, we assume that a new plot can only be cultivated if a farmer renounces another plot. They select the lowest quality plot, sell it, and eradicate the vines. No land market is modelled here; each plot is simply free when no farm owns it, while prices are defined by equation 4. Likewise, plots that are no longer suitable or profitable can be sold and become available for other purposes.

Buy high-quality plot

When farms have a planting right (e.g., acquired by selling a plot), they can buy a new plot and plant vines on it. They search for the most profitable available field nearby with quality higher than the quality standard. The vines' age is set to zero and age each year after the farm sells wine. A plot stays unproductive for three years. The average vines' age in each plot does not get above 20 years, assuming that the vineyard is maintained at an optimal age, ignoring old vines' substitution.

Abandon farming

Finally, if farms have registered negative profits in the previous five years, they will sell the least profitable. When only the farmstead plot is left, the farm agent exits.

GI Board action

Fees' collection and Marketing investment

First, the GI Board reshapes the GI area, defining which patch gets the GI label (important information for farms since it defines plots profitability and land prices). Then, it collects a fixed share (10%) of farms' revenues. The GI board makes no profits; half of its revenue is assumed to disappear in quality control and ensure standard compliance. The other half is spent in an endogenous brand value creation process. The Board invests in marketing to increase the collective brand value (CBV in equation 5), a form of intangible capital which behaves following a standard capital accumulation function. The value of the collective brand depreciates fast, by 40% each year (rho = 0.4), following literature on intangible capital (Corrado *et al.* 2020).

Update GI prestige and wine price

Finally, the Board updates the GI prestige level. The GI prestige can take five levels which depend on three variables: the collective brand value (the intangible capital stock described above), average wine quality from productive GI plots, and the percentage of farms producing GI wine. These three variables are divided into five levels/intervals, as Table 1 shows. Importantly, we set an arbitrary minimum value of collective brand value (named "basBrandValue" or "bbv") of 1000000 € to define the levels.

Table 1. Categorisation of main GI prestige variables into five levels.

	Level 0	Level 1	Level 2	Level 3	Level 4
GI quality	< 0.5	[0.5,0.7)	[0.7,0.8)	[0.8,0.9)	> 0.9
Collective brand value	< bbv	[bbv, 2*bbv)	[2*bbv, 3*bbv)	[3*bbv, 4*bbv)	> 4* bbv
% of GI farms	< 0.5	[0.5,0.7)	[0.7,0.8)	[0.8,0.9)	> 0.9

The average level of the three variables is rounded to the closest integer value and used as the GI prestige level. Increasing prestige level ensures a higher GI wine price, as in Table 2. Level 0 corresponds to the standard wine price.

Table 2. Prestige levels and respective GI wine price.

GI prestige	Level 0	Level 1	Level 2	Level 3	Level 4
GI wine price	1	1.5	2	2.5	3

It is essential to underline that the following framework is the result of arbitrary modeller choices. Both variables and the intervals set here have an important impact on the outcome. The three variables affecting GI prestige (i.e., a form of collective reputation) are inspired by theoretical literature on collective brand reputation (Fishman *et al.* 2018) and empirical studies on consumers' WTP for wine (Schamel 2009; Beckert *et al.* 2017), discussed in the previous chapters. The underlying idea is that a region can partially substitute average quality by consistently investing in other forms of intangible/symbolic capital embodied in the collective GI brand through marketing. Other than increasing total returns, the number of GI farms can also increase the signal provided to consumers.

Endogenous institutional change (collective-choice situation)

Farms can vote to change the quality standard: keep it constant, increase it, or decrease it. The delta variation achievable in each institutional change process is exogenously set to 1%. Institutional change is initiated every five years, a reasonable estimate for a long and centralised bureaucratic process. First, farms will vote to decrease the standard when they can no longer fulfil it in the current period. Then, they also retrieve the average wine quality achieved in the previous five years. If decreasing, they vote to lower the standard; otherwise, they vote to increase it only if a higher standard can be fulfilled. When no trend is shown in the previous years, farms will vote to keep the standard constant. Farms check trends by simply comparing the 5-year average quality with the present one and can sense quality variations in the order of 1%.

With the process described above, a farm-specific state variable called "ballot" is updated with value 1 (increase) -1 (decrease) or 0 (keep constant). Then ballots are collected in a list called "ballot-box". Votes are counted, and the final decision is taken depending on the exogenously defined voting mechanism. The ballot box is emptied at the end of the process.

4.2. Experimental design and model simulations

By using the BehaviorSpace tool in NetLogo, we run several simulations in which we systematically change levels of one exogenous variable (or factor) at a time. Three exogenous variables are considered: climate scenario, landscape heterogeneity, and voting mechanism (Table 3). The first two factors have two levels each: for climate scenarios, it is "Moderate" and "Strong" (i.e., +2°C, +3°C);

for landscape heterogeneity, it is relatively “heterogeneous” and “homogeneous” (i.e., with sigma (variance) of the Gaussian smoothing kernel of 1.5 and 3 respectively). Finally, we consider three different voting mechanisms on the institutional side: a no-vote baseline, a relative, and an absolute majority system. Therefore, we have an experimental design with a total of 2x2x3 = 12 combinations, each run 100 times, for a total of 1200 simulations. Each simulation runs for 55 years, and data is collected at each timestep. The first five years were removed from the data frame due to several variables’ “spin-up” effect starting from zero.

In the next section, we introduce the four output variables taken as proxies of the system’s climate resilience for our analysis, present and discuss the results attained.

Table 3. Three exogenous factors and corresponding levels driving the model’s simulations.

FACTORS	LEVELS		
Climate Scenario	+ 2°C	+ 3°C	
Landscape	sigma = 1.5 (heterogeneous)	sigma = 3.0 (homogeneous)	
Voting Mechanism	No Vote	ABS. Majority	REL. Majority

5. Results and Discussion

5.1. Results

This section presents and discusses the model's output relevant to our analysis. We analyse four variables to proxy the system's ability to preserve its main functions when facing climatic challenges (i.e., climate resilience). First, a cooperative viticultural system provides income to wine growers (i.e., private goods). Then, especially in the GI context, the combination of social and ecological factors (*terroir*) contributes to forming a collective reputation or value of the regional brand (i.e., common good). Third, viticultural activities help maintain the landscape and the local environment in good condition (i.e., public good). Such functional macro-categories are represented here by total farm exits and average profits, collective brand value, and a land-use index ratio based on total abandoned and acquired plots.

Table 4. Full factorial design matrix reporting all twelve factors' combinations (i.e., scenarios).

n.	Climate	Landscape	Voting Mechanism	Name	Colour
1	+ 2°C	Sigma = 1.5 (heterogenous)	AM (Absolute Majority)	2HetAM	**light blue**
2	+ 3°C	Sigma = 1.5	AM	3HetAM	**dark blue**
3	+ 2°C	Sigma = 3.0 (homogenous)	AM	2HomAM	**light green**
4	+ 3°C	Sigma = 3.0	AM	3HomAM	**dark green**
5	+ 2°C	Sigma = 1.5	NV (No Vote)	2HetNV	**pink**
6	+ 3°C	Sigma = 1.5	NV	3HetNV	**red**
7	+ 2°C	Sigma = 3.0	NV	2HomNV	**yellow**
8	+ 3°C	Sigma = 3.0	NV	3HomNV	**orange**
9	+ 2°C	Sigma = 1.5	RM (Relative Majority)	2HetRM	**lilac**
10	+ 3°C	Sigma = 1.5	RM	3HetRM	**purple**
11	+ 2°C	Sigma = 3.0	RM	2HomRM	**light brown**
12	+ 3°C	Sigma = 3.0	RM	3HomRM	**dark brown**

In Table 4, the full factorial design matrix of our experiment is presented. We abbreviate the names of each scenario to facilitate the analysis. For example, the scenario "2HetAM" stands for one with a milder temperature increase (+ 2°C), a relatively heterogeneous landscape and the possibility of changing the rule by absolute majority. Moreover, each scenario is assigned to a colour, with darker shades indicating "+3°C" climate change scenarios.

Figure 2 provides an overview of the main variables under scrutiny. Each line represents the within-scenario average, i.e., across 100 scenario-specific simulations. We plot data from period (year) five to limit confusion due to the spin-up of several variables (e.g., both total profits and collective brand value are set to zero at initialisation and jump to their maximum level around period 5).

Let us start from the first graph on the top left corner (Figure 2.a). "Farm exits" is a cumulative value expressed in percentage of the initial condition (N = 680 farms). We can distinguish a first outcome branch exhibiting high percentages of farm exits. These three scenarios (red, blue, and purple lines) are characterised by heterogeneity of landscape and strong climate change. As the climate is directly connected to wine quality in the model, this comes with no surprise: the higher the temperature increase, the lower farms' wine quality, increasing the risk of breaching the standard and losing the GI label that makes the business viable.

Moreover, the standard is particularly limiting in cases of high spatial heterogeneity. Heterogeneity increases the average slope value and production costs per hectare, thus the importance of accessing higher premia to stay in business (i.e., using the GI label). For this branch, the endogenous rule change process starts producing effects around period 33, when farms collectively decide to decrease the GI quality standard. The result is a substantial difference within the "3Het" branch in average farm exit values at period 55, with the no-vote (NV, in red) still increasing over 50%, and the two absolute (AM, in blue) and relative majority (RM, in violet) scenarios levelling at around 30% of the original population.

The "3Hom" combinations follow a pattern similar to the "3Het" case. We see a large spread between the NV (orange) and the AM/RM subcases (green and brown), initially steeper concave curves, with farm exits gradually slowing down. On the other hand, all moderate climate change scenarios exhibit convex curves with the lowest exit rates for most of the period considered. Endogenous rule changing does not produce any noticeable effect in both "2Het" and "2Hom" branches. As earlier, spatial heterogeneity hurts farms survival capacity.

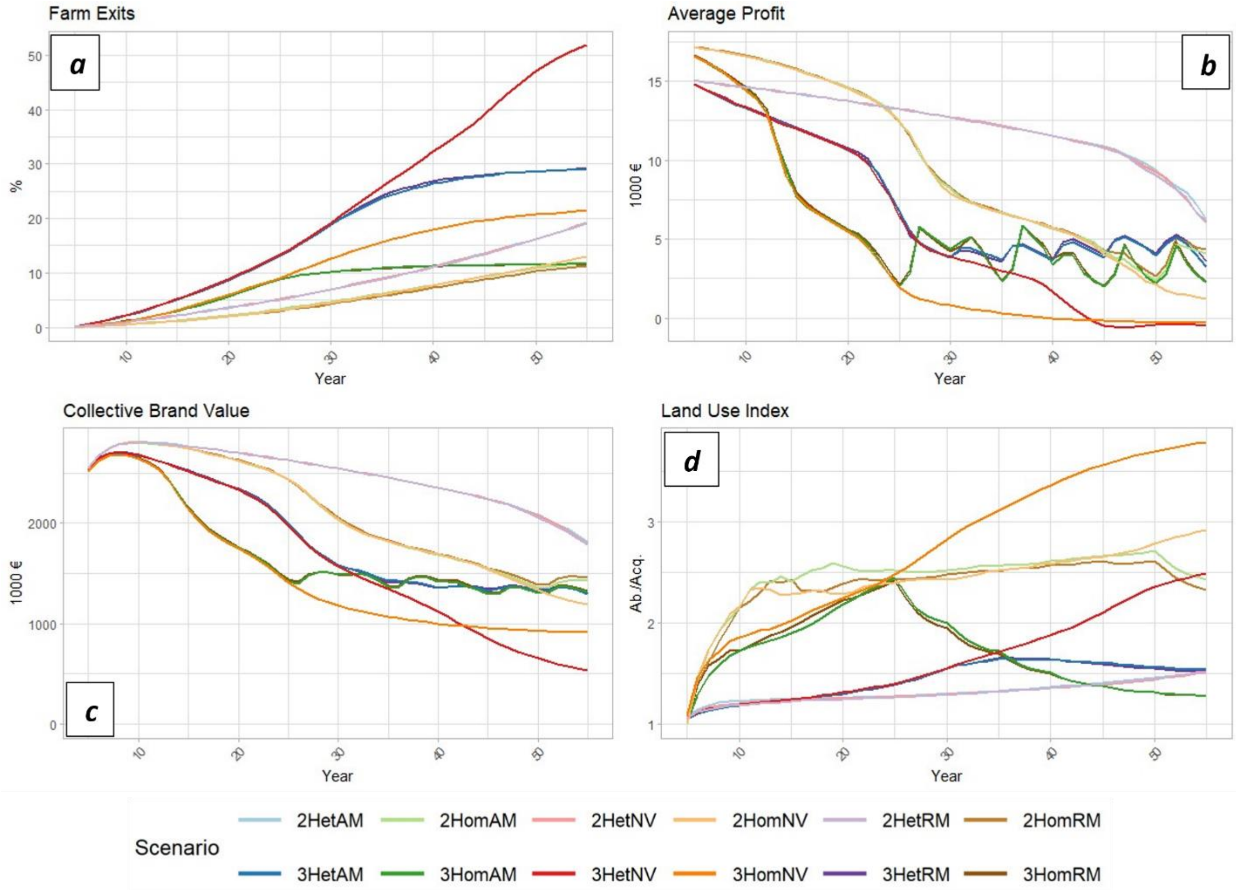


Figure 3. Resilience indicators, average across 100 simulations for each one of the twelve scenarios.

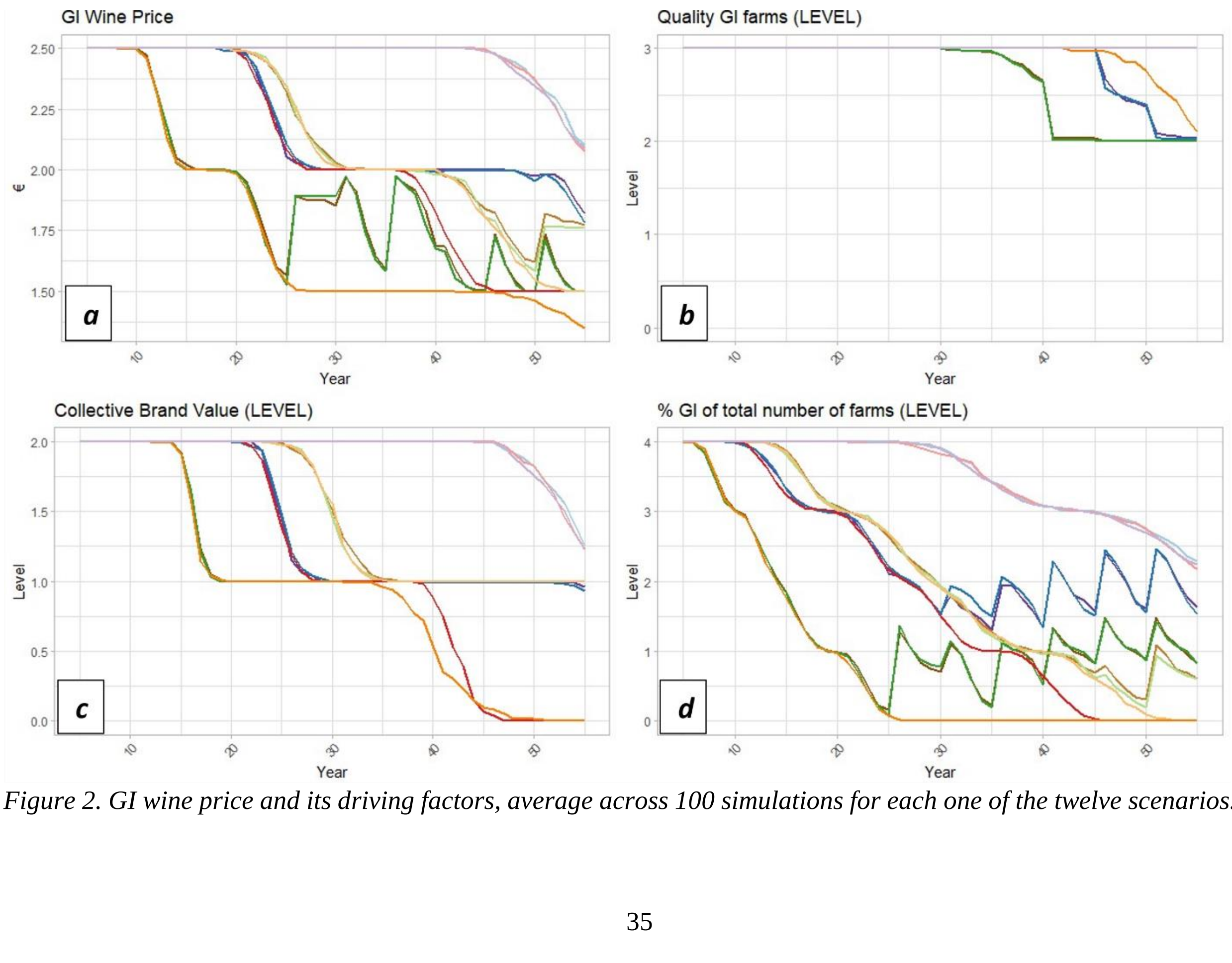


Figure 2. GI wine price and its driving factors, average across 100 simulations for each one of the twelve scenarios.

Can we say anything about the effect of different voting mechanisms (i.e., AM and RM scenarios)? No. Even though AM sub-cases are slightly above the RM ones, but only in the harshest climate scenario. We expected rule amendment to be more successful in the RM scenario, especially with high spatial heterogeneity, but this is not shown in the results. On the other hand, we observe that institutional change (i.e., the decrease of the production standard) happens only with homogeneous landscapes in the moderate climate scenario. In fact, we can see a narrow spread in between NV (yellow) and AM/RM (light green and light brown) sub-cases in the "2Hom" branch.

Average profits and collective brand value are expressed in thousands of euros. Here, we can better appreciate some emerging patterns driven by endogenous institutional change. In the first 25 years of the simulation, Figure 2.b, shows four main branches marked by different climate and landscape factor combinations. In all homogenous landscape scenarios, profits reach the maximum due to low average slope and production costs per hectare. On the other hand, although landscape heterogeneity leads to lower profits in the short-run (keeping the climate constant), it maintains higher profits for a longer time (see branch yellow vs lilac and orange vs red). As expected, landscape heterogeneity improves individual farms' adaptability by increasing the portion of new suitable land around them.

Not surprisingly, the stronger the climate change, the faster profits drop in both landscape configurations (see branch yellow vs orange and lilac vs red). Things get complex after year 25 when institutional change starts to be effective. Stronger climate scenarios are primarily affected, starting from the "3Hom" branch at tick 25. In this case, institutional change causes profits to fluctuate widely. The underlying intuition is that, by decreasing the quality standard, more farms can keep the GI label, access the higher price and increase average profitability. On the other hand, climate change is fast in these setups, and it immediately puts pressure back onto farms that rapidly lose the GI and experience a drop in profitability until a new agreement on decreasing the standard is found.

In the "3Het" branch, a collective decision on decreasing the standard is only found from tick 30 onwards. This can be for two main reasons: the first, heterogeneity of landscape, implies heterogeneity of impacts, making it arduous to find an agreement; the second, spatial heterogeneity increases individual adaptive capacity, reducing or delaying the need for collective action. This should be further tested by limiting individual adaptive capacity in the model. Finally, institutional change comes only late (year 50) in the more optimistic climate scenarios and only with homogeneous landscapes.

Production is fixed at 5000 litres/ha, and demand is assumed to cover supply (see section 4.1.5). Thus, the main driver for average profit is the GI wine price. The relevance of price comes clear in figure 3.a. First, prices drop around tick 12 and 22 causing falling total profits in the "3Hom" and "3Het" branches. The same occurs again after tick 20 and 37 (see orange and red lines), dragging down profits further. The price fluctuation also causes the emergence of the oscillatory patterns for scenarios "3HomAM" (green), "3HomRM" (brown), "3HetAM", and "3HetRM", and we also understand why the former two appear wavier than the latter. In fact, prices are on average stable in the "3Het" branch between tick 25 and 50, while the opposite emerges in the "3Hom" branch. Decomposing price into its three steering factors helps understanding how these oscillations emerge. First, quality plays a role in the definition of price only in the strong climate scenario. Interestingly, the quality level is constant in the "3HetNV" scenario, meaning that the few remaining farms managed to use the microclimatic landscape diversity to maintain high quality (Figure 3.b). The level of collective brand value stays constant from period 20 to 55 for all scenarios except "3HomNV" and "3HetNv". On the other hand, the level of percentage share of GI farms (i.e., given by the % of GI farms over the total number of farms) appears to be causing the oscillating profit patterns.

The reader should be reminded that these level variables are integers ranging from 0 to 4 (see section 4.1.5). The oscillation between levels 0 and 1 of % share of GI farms causes major disbalances in the price, affecting profitability in the green and brown scenarios. On the other hand, in the blue and purple cases, the oscillation between level 1 and 2 does not affect the price. However, it implies a variable portion of farms allowed to use the GI label, thus causing those "smoother waves" seen in Figure 2.b.

Moving to Figure 2.c, we can say that collective brand value closely follows the previous profits dynamics, mainly price-driven. The "2Het" branch achieves the best results consistently through time. Consequently, endogenous rule change prevents profits falling under 1M €, unlike when fast climatic change and no voting opportunity are considered.

Finally, in Figure 2.d, the ratio of total cumulative abandoned to acquired land is shown. The index indicates whether the original viticultural landscape is endangered. Three out of four "NV" scenarios led to the three highest index levels, where abandoned land at year 55 is around 3.7, 3, and 2.5 times greater than the newly acquired portion (see orange, yellow, and red lines). The ample spread within the "3Hom" branch caused by endogenous institutional change is the first to capture the attention. Plots are abandoned for three reasons in the model: substitution with higher quality land, unprofitability, and farm exit. Land can be easily substituted when the landscape is heterogenous, the reason why most “Het” scenarios occupy the lower region of the graph. In the “3HomNV” scenario, we see that the index tracks farm exits, at least in the second half of the simulation, indicating that farm exits is the driving factor for land abandonment from around period 20 onwards. This intuition is confirmed when looking at the “3Het” and the “2Het” branches. In year 25, the quality standard starts being amended in the “3Hom” branch. We see how the two scenarios with institutional change (green and brown lines) take a diverging path leading the index to its local minimum at tick 55. The “3Hom” branch is the most successful in terms of the number of rule amendments. Decreasing the standard broadens the availability of newly suitable plots, farms re-start cultivating land, plummeting the index (see dark green and dark brown lines in figure 2.d).

Unexpectedly, in the first half of the simulation, the land index for the “2Hom” branch rises the fastest (yellow, light brown and light green lines). We expected the “3Hom” branch to be the highest in these cases given the reasons already discussed. Figure 4 shows the complete data for the land use index with punctual observation for each simulation at each period (see appendix 2 for similar graphs of the other variables). Colours and line/dot types represent climate and landscape factors, while facets are used for different voting mechanisms sub-samples. See the presence of several outliers in the “2Hom” scenarios (green crosses) in both institutional change setting. Decomposing the number of abandoned hectares by cause (i.e., farm exit, unprofitability, and substitution) clarified that these outliers are characterised by low substitution and high abandonment for unprofitability and farm exit. The reason why mainly “2Hom” scenarios are affected is most likely that in this scenario, climate change is too slow to urge farms to adapt by substituting land, which would shrink the index’s denominator (i.e., newly acquired plots). Eventually, when farms start noticing a decrease in quality and substituting land (year 20), the index levels out at around 2.5.

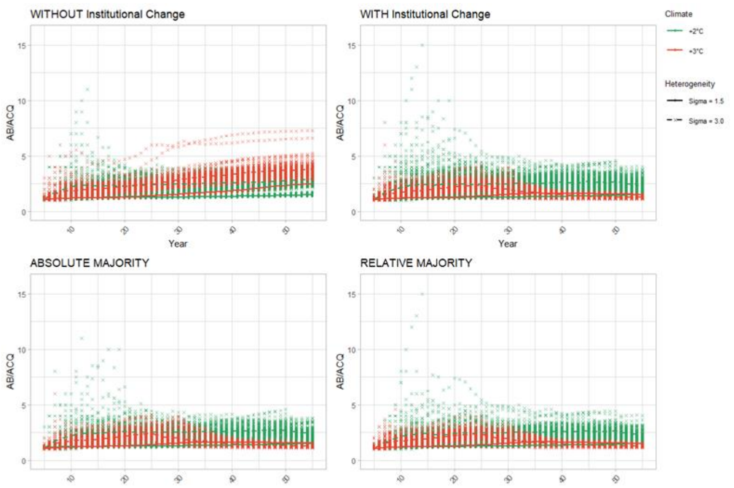


Figure 4. Land Use Index, full data for different voting mechanisms.

For completeness and to give an idea of within-scenario variability, figure 5 offers a boxplot representation of the four main output variables for years 5, 15, 25, 35, 45, and 55. The asterisk sign represents the mean within 100 simulations for each one of the twelve scenarios at each point in time. On the other hand, the coloured lines connect the median of each scenario at each point in time (i.e., the central line of each boxplot). Finally, Table 5 reports the mean and standard deviation for each scenario at period 55. Appendix 3 offers a more detailed representation of the distribution of these variables at the end of the simulation.

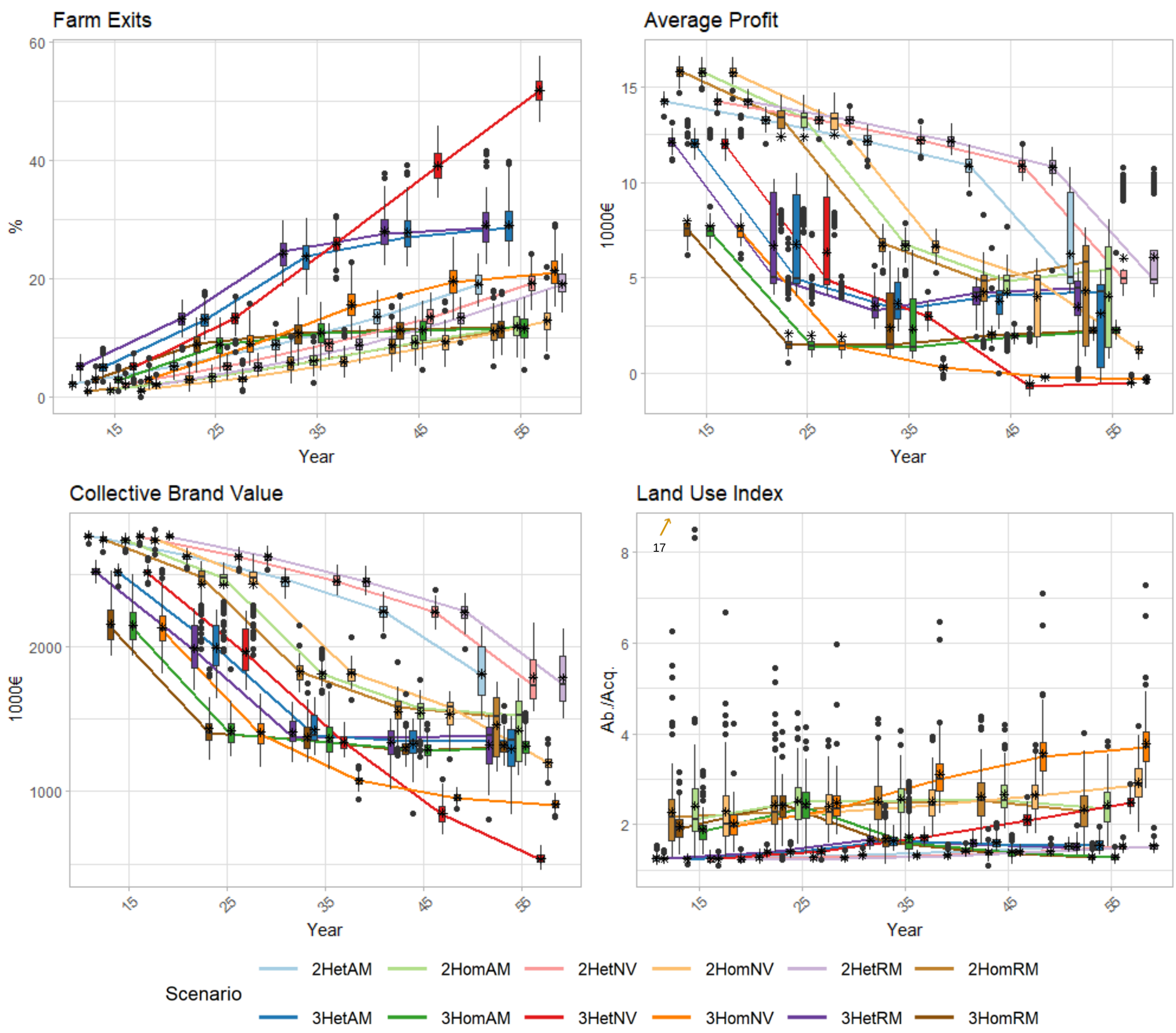


Figure 5. Boxplot representation of the four main output variables for six representative years.

Table 5. Mean and Standard Deviation of main outcome variables for each scenario at period 55.

SCENARIO		FARM EXITS		MEAN PROFITS		COLLECTIVE BRAND VALUE		GI WINE PRICE		LAND INDEX	
NAME	**COLOUR**	**MEAN**	**SD**	**MEAN**	**SD**	**MEAN**	**SD**	**MEAN**	**SD**	**MEAN**	**SD**
2HetAM	light blue	19.072	2.110	6.250	2.263	1812.954	186.591	2.100	0.201	1.517	0.085
3HetAM	dark blue	29.097	3.897	3.161	2.032	1296.640	165.415	1.780	0.249	1.538	0.128
2HomAM	light green	11.904	2.096	4.048	2.670	1424.901	213.095	1.760	0.251	2.429	0.500
3HomAM	dark green	11.629	2.467	2.298	0.463	1316.814	70.870	1.500	0.000	1.282	0.080
2HetNV	pink	19.259	2.072	6.042	2.139	1790.261	176.444	2.075	0.179	1.516	0.080
3HetNV	red	51.815	2.300	-0.462	0.128	534.655	34.437	1.500	0.000	2.488	0.137
2HomNV	yellow	12.994	2.417	1.241	0.232	1196.196	52.684	1.500	0.000	2.920	0.442
3HomNV	orange	21.381	3.137	-0.302	0.039	910.585	34.922	1.350	0.230	3.782	0.676
2HetRM	lilac	19.156	2.118	6.098	2.219	1787.310	185.587	2.090	0.193	1.524	0.092
3HetRM	purple	29.069	3.837	3.506	1.963	1322.049	159.852	1.820	0.241	1.518	0.122
2HomRM	light brown	11.185	2.333	4.320	2.609	1459.680	205.253	1.775	0.250	2.329	0.496
3HomRM	dark brown	11.578	2.191	2.273	0.251	1321.344	74.744	1.500	0.000	1.280	0.078

5.2. Discussion

The model's results highlight a possible twofold role of landscape heterogeneity on the climate resilience of the system. First, landscape heterogeneity improves individual farms' adaptive capacity. In other words, it allows relocating vineyards to high elevation plots where a cooler microclimate guarantees a better wine quality. Several viticultural regions in Europe have already climbed the mountains around them to adapt to higher temperatures, and this is a typical adaptation process that will continue in the future (Moriondo *et al.* 2013; Gutiérrez-Gamboa *et al.* 2021). Second, although a heterogeneous landscape accelerates farm exits due to higher production costs, we have shown how it also helps the system to achieve higher and more stable profits throughout the simulation.

On the other hand, heterogeneity might also slow down collective decision making. This is because, within scenarios allowing for endogenous institutional change, heterogeneous landscape settings were less likely to result in decreasing the quality standard, exhibiting a delayed onset of the rule amendment process. In milder climate change scenarios, institutional change was generally not adopted by farms, except for the homogenous settings around the end of the simulation, confirming our point.

Cooperative systems already suffer from different forms of member heterogeneity, leading to diversity of member's interests and objectives (Höhler & Kühl 2017). Heterogeneity can lead to low willingness to cooperate among members, incentivise free-riding, and the emergence of social dilemmas. The model ignores moral hazard and opportunistic behaviours in the operational arena (e.g., to declare untruthful information on wine quality at delivery). Nonetheless, our results underline that social dilemmas do not affect the operational area only and might also emerge in the collective-choice arena where farms decide how to shape their institutional environment and constraints. Lowering standards helps many remain in business but might also damage those who can individually cope with climate change. To some extent, the model hints at the existence of incentives to leave the cooperative for the best performing and most adaptive farms, possibly another example of self-selection of cooperative members leading to poor collective performances (Castriota 2020 p. 176). However, we did not model the possibility of single farms delivering grapes to other companies, expanding, investing in private brands, and creating individual standards. Therefore, we leave exploring these mechanisms to future research, in which cooperatives and corporations could be confronted, and cooperatives' and GI consortium's boards separated accordingly.

When farms were enabled to engage in endogenous institutional change, considerable variations in our target variables were recorded, including the emergence of complex/chaotic behaviours. This only applies to the "+ 3°C" climate change scenario, which is arguably the most relevant if climate action continues to fail. Different voting mechanisms did not show significant differences in the outcome. The two one-farm-one-vote systems are probably too similar. New voting mechanisms and governance structures could be tested in future model development by looking at literature on cooperatives (Chaddad & Cook 2004; Bijman *et al.* 2014).

The quality standard was never increased in the 1200 simulations performed. However, a few parameters (e.g., memory, farms' precision, and quality delta) play an essential role in this process and should be tested with a systematic sensitivity analysis. In fact, during model debugging, we could observe that increasing memory and precision can enhance amendment effectiveness and cause the standard to fluctuate (i.e., increase and decrease). This also has interesting policy implications, for example, concerning investments in information sharing and quality monitoring which could have significant repercussions on the institutional change process.

Lowering, or changing, quality standards as a possible adaptation measure might be a slippery slope. In fact, changing quality might betray consumers expectations, reduce reputation and willingness to pay. In our model, we introduced investments in intangibles as a compensating measure for quality reduction/change. These two actions complement each other and should be planned carefully, improving synergies between them.

More specifically, we explored the possibility for the GI system to substitute quality with intangible capital to maintain a high collective reputation/prestige and high premia. We exemplify this by modelling the role of marketing investments and collective brand value in a price formation module. However, this could also be regarded as a general expenditure in intangibles, including research and development, climate-smart technologies. This option was available and employed by the GI board in the model. However, as discussed in the previous chapters, in reality, cooperatives suffer from low investment capability, especially in intangible assets. This might significantly limit their ability to use this adaptation option which is a vital complement to the institutional adaptation of production/quality standards.

Total profits and collective brand value were the highest in the "2Het" branch, and those scenarios allowing for endogenous institutional change. Due to the specific model assumptions (i.e., GI board simply investing a fixed share of total revenues), profits and brand value are closely related. In the future, the GI board agent should be given a more sophisticated decision-making heuristic (e.g., maximising brand value while keeping high compliance incentives for farms) which could substantially change our results.

Introducing the effect of the percentage share of GI farms in the area on prestige and GI price led to the emergence of oscillating prices. These results raise a few concerns about the arbitrariness of this price formation mechanism. Although the idea is to represent the importance of intangibles (brand value) (Beckert *et al.* 2017), the level (GI farms' quality) (Schamel 2009) and the strength (GI farms quota) (Fishman *et al.* 2018) of reputational quality signals on wine price, the choice of this particular level setup are perhaps the most critical limitations of this study. However, it was not easy to find parameters in the literature to calibrate such a mechanism. For example, what is the basic level of cumulative intangible expenditure (collective brand value) that guarantees higher GI wine premia? Using our model for future empirical studies, presume the careful calibration of a better prestige/reputation and price formation module, including the exploration of new driving factors. Moreover, if farms' opportunistic behaviour and costly rule control and punishment were modelled, the effect of the total share of GI farms would have to be reconsidered. In that case, the more farms, the higher the chance of opportunistic behaviours to emerge and the cost of controlling for the GI board (Fishman *et al.* 2018).

Finally, we used a simple land use index to evaluate the role of spatial heterogeneity and endogenous institutional change on land abandonment. We can conclude that heterogeneous landscapes might help maintain the original size of the viticultural area, backing the concept that diversity, in all its forms, is a supporting condition for resilience (Folke *et al.* 2010; Folke 2016). On the other hand, allowing institutional change effectively reduced the ratio between abandoned and newly acquired plots. However, the index is too general to say anything about the preservation of the original viticultural landscape. More sophisticated landscape heterogeneity indices, e.g., looking at the aggregation of contiguous vineyards, should be analysed in the future. Moreover, this result is also highly influenced by our choice of allowing new land acquisition only through substitution of no longer suitable plots. An improved land and planting rights market should be introduced in the future, also allowing best performing farms to expand.

Nevertheless, our simple observation calls for further research into the effect of contrasting agricultural interests/purposes in a region. Even if landscape heterogeneity and institutional change increase the possibility of converting new plots to viticulture, the model completely ignores the previous use of those plots, whether they were protected ecological areas or necessary for another agricultural purpose.

The absence of a systematic sensitivity analysis on the main parameters should warn the reader to interpret our results critically. This also limits the use of inference and statistical hypothesis testing on this data which, in our case, would only be misleading.

6. Conclusions

European viticulture is particularly vulnerable to potential climate effects on GI. Small farms have little capacities to predict climatic impacts and select effective adaptation practices. Furthermore, several wine-making territories in Europe are controlled by cooperatives that rely on GI collective brands due to low investing capacity in intangibles and private brands.

Drawing from institutional economics theory and literature on cooperatives and collective brand, we created a novel theoretical model with endogenous institutional change to explore the climate resilience of cooperative GI viticultural systems in the EU.

As the main objective of the thesis, we explored the effect of different institutional (i.e., voting mechanisms) and environmental (i.e., landscape heterogeneity) settings on climate resilience in terms of the system's ability to maintain its main functions (i.e., providing private, collective, and public goods). Farm exits, average profit, collective brand value, and a land abandonment index were used as proxies for those functions.

We compared the average output of 100 simulations for each of the 12 factors' combinations. The inclusion of endogenous institutional change led to considerable variations in all target variables, including the emergence of complex/chaotic behaviours. It enabled the system to reduce farm exits, increase profitability and collective brand value. We showed how landscape heterogeneity has a twofold role in the climate resilience of the system. It increases individual adaptability but obstructs collective adaptive capacity through institutional change. The two different voting mechanisms considered (i.e., relative and absolute majority) did not produce any discernible result.

The model has several limitations, especially regarding few arbitrary choices made in the context of the price formation mechanism. The representation of GI board behaviour, which applies a standard rule without making any actual decision, is also highly simplistic. Moreover, the lack of a systematic sensitivity analysis warns the reader to interpret these results critically. Several parameters have a significant impact on model outcomes and should be tested in the future.

Future model development is necessary to implement better price formation mechanisms and introduce a slightly more sophisticated land and land-use module. Second, different voting mechanisms could be tested, comprising the possibility for farms to cooperate/communicate, form networks and alliances. Further, new resilience indicators could be developed, exploring dimensions of diversity, redundancy, and interconnectedness. Finally, it would be interesting to include both cooperative farms and private companies and explore more complex interactions between different agent types in the GI production system.

The model is comprehensively documented and freely available online. We used a multidisciplinary approach to build a flexible theoretical model adaptable to different study sites with the necessary modifications. This research also contributes to developing literature on considering endogenous institutional change as a climate change adaptation option in agricultural systems, connecting climate impact, institutional, and agricultural economics studies through agent-based modelling.

Our results cannot be used to predict any real case scenario or inform specific policies. They are proofs of concept that stimulate further empirical research, especially in the role of environmental heterogeneity and institutional setting on climate resilience when allowing for endogenous institutional change. This work can interest wine GI production regions and other agricultural systems based on collective reputations and quality standards impacted by climate change. Even though we cannot make any case-specific policy recommendation, in general, we highlighted the importance of policies oriented to strengthening investments in intangibles and facilitating GI rule amendments, especially in sectors where cooperatives predominate due to poor intangible investments capability and other issues connected to member heterogeneity.

Using data to calibrate the model and relax theoretical assumption could generate important empirical findings on the impact of different social, institutional and environmental settings on local climate resilience and inform climate change adaptation policies.

References

Amadieu, P., Maurel, C. & Viviani, J.-L. (2013). Intangibles, Export Intensity, and Company Performance in the French Wine Industry. *Journal of Wine Economics*, vol. 8 (2), pp. 198–224. DOI: https://doi.org/10.1017/jwe.2013.27

Amadieu, P. & Viviani, J.L. (2011). Intangible expenses: a solution to increase the French wine industry performance? *European Review of Agricultural Economics*, vol. 38 (2), pp. 237–258. DOI: https://doi.org/10.1093/erae/jbr012

Antonelli, G. & Vigano, E. (2012). Il ruolo dei marchi di qualità dell'Unione Europea nelle strategie competitive delle piccole e medie imprese agroalimentari italiane. *Piccola Impresa / Small Business*, vol. 0 (3), pp. 16–17. DOI: https://doi.org/https://doi.org/10.14596/pisb.31

Ashenfelter, O. & Storchmann, K. (2016). The Economics of Wine, Weather, and Climate Change. *Review of Environmental Economics and Policy*, vol. 10 (1), pp. 25–46. DOI: https://doi.org/10.1093/reep/rev018

Beckert, J., Rössel, J. & Schenk, P. (2017). Wine as a Cultural Product. *Sociological Perspectives*, vol. 60 (1), pp. 206–222. DOI: https://doi.org/10.1177/0731121416629994

Belletti, G., Marescotti, A. & Touzard, J.-M. (2017). Geographical Indications, Public Goods, and Sustainable Development: The Roles of Actors' Strategies and Public Policies. *World Development*, vol. 98, pp. 45–57 Elsevier Ltd. DOI: https://doi.org/10.1016/j.worlddev.2015.05.004

Bernetti, I., Menghini, S., Marinelli, N., Sacchelli, S. & Sottini, V.A. (2012). Assessment of climate change impact on viticulture: Economic evaluations and adaptation strategies analysis for the Tuscan wine sector. *Wine Economics and Policy*, vol. 1 (1), pp. 73–86 Elsevier. DOI: https://doi.org/10.1016/j.wep.2012.11.002

Bijman, J., Hanisch, M. & van der Sangen, G. (2014). Shifting control? The changes of internal governance in agricultural cooperatives in the EU. *Annals of Public and Cooperative Economics*, vol. 85 (4), pp. 641–661. DOI: https://doi.org/10.1111/apce.12055

Bijman, J., Iliopoulos, C., Poppe, K.J., Gijselinckx, C., Hagedorn, K., Hanisch, M., Hendrikse, G.W.J., Kühl, R., Ollila, P., Pyykkönen, P. & Sanger, G.V. DER (2012). Support for farmers' cooperatives. *Sector Report Fruit and Vegetables, Wageningen Wageningen UR*, p. 127

Castriota, S. (2020). *Wine Economics*. *Wine Economics* The MIT Press. DOI: https://doi.org/10.7551/mitpress/11106.001.0001

Chaddad, F.R. & Cook, M.L. (2004). Understanding new cooperative models: An ownership-control rights typology. *Review of Agricultural Economics*, vol. 26 (3), pp. 348–360. DOI: https://doi.org/10.1111/j.1467-9353.2004.00184.x

Clark, L.F. & Kerr, W.A. (2017). Climate change and terroir : The challenge of adapting geographical indications. *The Journal of World Intellectual Property*, vol. 20 (3–4), pp. 88–102. DOI: https://doi.org/10.1111/jwip.12078

Corrado, C., Haskel, J., Iommi, M. & Jona-Lasinio, C. (2020). Intangible capital, innovation, and productivity à la Jorgenson evidence from Europe and the United States. *Measuring Economic Growth and Productivity*. Elsevier, pp. 363–385.

Crawford, S.E.S. & Ostrom, E. (1995). A Grammar of Institutions. *American Political Science Review*, vol. 89 (3), pp. 582–600. DOI: https://doi.org/10.2307/2082975

Delay, E., Piou, C. & Quenol, H. (2015). The mountain environment, a driver for adaptation to climate change. *Land Use Policy*, vol. 48, pp. 51–62 Elsevier Ltd. DOI: https://doi.org/10.1016/j.landusepol.2015.05.008

Droulia, F. & Charalampopoulos, I. (2021). Future Climate Change Impacts on European Viticulture: A Review on Recent Scientific Advances. *Atmosphere*, vol. 12 (4), p. 495. DOI: https://doi.org/10.3390/atmos12040495

Edelmann, H., Quiñones-Ruiz, X.F., Penker, M., Scaramuzzi, S., Broscha, K., Jeanneaux, P., Belletti, G. & Marescotti, A. (2020). Social Learning in Food Quality Governance – Evidences from Geographical Indications Amendments. *International Journal of the Commons*, vol. 14 (1), pp. 108–122. DOI: https://doi.org/10.5334/ijc.968

Fishman, A., Finkelstein, I., Simhon, A. & Yacouel, N. (2018). Collective brands. *International Journal of Industrial Organization*, vol. 59, pp. 316–339 Elsevier B.V. DOI: https://doi.org/10.1016/j.ijindorg.2018.03.002

Folke, C. (2016). Resilience (Republished). *Ecology and Society*, vol. 21 (4), p. art44. DOI: https://doi.org/10.5751/ES-09088-210444

Folke, C., Carpenter, S.R., Walker, B., Scheffer, M., Chapin, T. & Rockström, J. (2010). Resilience Thinking: Integrating Resilience, Adaptability and Transformability. *Ecology and Society*, vol. 15 (4), p. art20. DOI: https://doi.org/10.5751/ES-03610-150420

Gori, C. & Alampi Sottini, V. (2014). The role of the Consortia in the Italian wine production system and the impact of EU and national legislation. *Wine Economics and Policy*, vol. 3 (1), pp. 62–67 Elsevier. DOI: https://doi.org/10.1016/j.wep.2014.05.001

Gutiérrez-Gamboa, G., Zheng, W. & Martínez de Toda, F. (2021). Strategies in vineyard establishment to face global warming in viticulture: a mini review. *Journal of the Science of Food and Agriculture*, vol. 101 (4), pp. 1261–1269. DOI: https://doi.org/10.1002/jsfa.10813

Hausfather, Z. & Peters, G.P. (2020). Emissions – the 'business as usual' story is misleading. *Nature*, vol. 577 (7792), pp. 618–620. DOI: https://doi.org/10.1038/d41586-020-00177-3

Höhler, J. & Kühl, R. (2017). Dimensions of member heterogeneity in cooperatives and their impact on organization - A literature review. *Annals of Public and Cooperative Economics*, vol. 89 (4), pp. 697–712. DOI: https://doi.org/10.1111/apce.12177

Huber, R., Bakker, M., Balmann, A., Berger, T., Bithell, M., Brown, C., Grêt-Regamey, A., Xiong, H., Le, Q.B., Mack, G., Meyfroidt, P., Millington, J., Müller, B., Polhill, J.G., Sun, Z., Seidl, R., Troost, C. & Finger, R. (2018). Representation of decision-making in European agricultural agent-based models. *Agricultural Systems*, vol. 167 (September 2017), pp. 143–160 Elsevier. DOI: https://doi.org/10.1016/j.agsy.2018.09.007

IPCC (2018). *Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A.

Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. World Meteorological Organization, Geneva, Switzerland,.

Jones, G. V., White, M.A., Cooper, O.R. & Storchmann, K. (2005). Climate Change and Global Wine Quality. *Climatic Change*, vol. 73 (3), pp. 319–343. DOI: https://doi.org/10.1007/s10584-005-4704-2

Meuwissen, M.P.M., Feindt, P.H., Spiegel, A., Termeer, C.J.A.M., Mathijs, E., Mey, Y. de, Finger, R., Balmann, A., Wauters, E., Urquhart, J., Vigani, M., Zawalińska, K., Herrera, H., Nicholas-Davies, P., Hansson, H., Paas, W., Slijper, T., Coopmans, I., Vroege, W., Ciechomska, A., Accatino, F., Kopainsky, B., Poortvliet, P.M., Candel, J.J.L., Maye, D., Severini, S., Senni, S., Soriano, B., Lagerkvist, C.-J., Peneva, M., Gavrilescu, C. & Reidsma, P. (2019). A framework to assess the resilience of farming systems. *Agricultural Systems*, vol. 176 (May), p. 102656 Elsevier. DOI: https://doi.org/10.1016/j.agsy.2019.102656

Moriondo, M., Jones, G. V., Bois, B., Dibari, C., Ferrise, R., Trombi, G. & Bindi, M. (2013). Projected shifts of wine regions in response to climate change. *Climatic Change*, vol. 119 (3–4), pp. 825–839. DOI: https://doi.org/10.1007/s10584-013-0739-y

Mozell, M.R. & Thach, L. (2014). The impact of climate change on the global wine industry: Challenges & solutions. *Wine Economics and Policy*, vol. 3 (2), pp. 81–89. DOI: https://doi.org/10.1016/j.wep.2014.08.001

Müller, B., Bohn, F., Dreßler, G., Groeneveld, J., Klassert, C., Martin, R., Schlüter, M., Schulze, J., Weise, H. & Schwarz, N. (2013). Describing human decisions in agent-based models – ODD + D, an extension of the ODD protocol. *Environmental Modelling & Software*, vol. 48, pp. 37–48. DOI: https://doi.org/10.1016/j.envsoft.2013.06.003

OIV (2021). *State of the world vitivinicultural sector in 2020* Available at: https://www.oiv.int/public/medias/7909/oiv-state-of-the-world-vitivinicultural-sector-in-2020.pdf [2021-05-19]

Ostrom, E. (2009). *Understanding institutional diversity*. Princeton university press.

Pomarici, E. & Sardone, R. (2020). EU wine policy in the framework of the CAP: post-2020 challenges. *Agricultural and Food Economics*, vol. 8 (1), p. 17 Agricultural and Food Economics. DOI: https://doi.org/10.1186/s40100-020-00159-z

Poteete, A.R., Janssen, M.A. & Ostrom, E. (2010). *Working together: Collective action, the commons, and multiple methods in practice*. Princeton university press.

Quiñones Ruiz, X.F., Forster, H., Penker, M., Belletti, G., Marescotti, A., Scaramuzzi, S., Broscha, K., Braito, M. & Altenbuchner, C. (2018). How are food Geographical Indications evolving? – An analysis of EU GI amendments. *British Food Journal*, vol. 120 (8), pp. 1876–1887. DOI: https://doi.org/10.1108/BFJ-02-2018-0087

Sacchelli, S., Fabbrizzi, S., Bertocci, M., Marone, E., Menghini, S. & Bernetti, I. (2017). A mix-method model for adaptation to climate change in the agricultural sector: A case study for Italian wine farms. *Journal of Cleaner Production*, vol. 166, pp. 891–900 Elsevier Ltd. DOI: https://doi.org/10.1016/j.jclepro.2017.08.095

Santos-Arteaga, F.J. & Schamel, G. (2018). Organizational Form and Payoff Imbalances in an Aggrievement Model: Cooperatives versus Privately Owned Wineries. *Journal of Wine Economics*, vol. 13 (3), pp. 263–281. DOI: https://doi.org/10.1017/jwe.2018.32

Schamel, G. (2009). Dynamic Analysis of Brand and Regional Reputation: The

Case of Wine. *Journal of Wine Economics*, vol. 4 (1), pp. 62–80 Cambridge University Press. Available at: https://ideas.repec.org/a/cup/jwecon/v4y2009i01p62-80_00.html [2021-05-18]
Schamel, G.H. (2015). Can German wine cooperatives compete on quality? (Aurand, J.-M., ed.) *BIO Web of Conferences*, vol. 5, p. 03003. DOI: https://doi.org/10.1051/bioconf/20150503003
Schulze, J., Müller, B., Groeneveld, J. & Grimm, V. (2017). Agent-Based Modelling of Social-Ecological Systems: Achievements, Challenges, and a Way Forward. *Journal of Artificial Societies and Social Simulation*, vol. 20 (2). DOI: https://doi.org/10.18564/jasss.3423
Sellers-Rubio, R., Mas-Ruiz, F. & Sancho-Esper, F. (2018). Firm reputation, advertising investment, and price premium: The role of collective brand membership in high-quality wines. *Agribusiness*, vol. 34 (2), pp. 351–362. DOI: https://doi.org/10.1002/agr.21526
Sellers-Rubio, R., Mas-Ruiz, F. & Sancho-Esper, F. (2021). Reputation and Advertising of Collective Brand Members in the Wine Industry: The Moderating Role of Market Share. *Journal of Wine Economics*, pp. 1–20. DOI: https://doi.org/10.1017/jwe.2020.52
Smajgl, A., Izquierdo, L.R. & Huigen, M. (2008). Modeling endogenous rule changes in an institutional context: The adico sequence. *Advances in Complex Systems*, vol. 11 (2), pp. 199–215
Storchmann, K. (2018). Introduction to the Issue: Wine Cooperatives. *Journal of Wine Economics*, vol. 13 (3), pp. 239–242. DOI: https://doi.org/10.1017/jwe.2018.51
Sun, Z., Lorscheid, I., Millington, J.D., Lauf, S., Magliocca, N.R., Groeneveld, J., Balbi, S., Nolzen, H., Müller, B., Schulze, J. & Buchmann, C.M. (2016). Simple or complicated agent-based models? A complicated issue. *Environmental Modelling & Software*, vol. 86 (3), pp. 56–67 Elsevier Ltd. DOI: https://doi.org/10.1016/j.envsoft.2016.09.006
Taghikhah, F., Filatova, T. & Voinov, A. (2021). Where Does Theory Have It Right? A Comparison of Theory-Driven and Empirical Agent Based Models. *Journal of Artificial Societies and Social Simulation*, vol. 24 (2). DOI: https://doi.org/10.18564/jasss.4573
Thiele, J.C. & Grimm, V. (2010). NetLogo meets R: Linking agent-based models with a toolbox for their analysis. *Environmental Modelling & Software*, vol. 25 (8), pp. 972–974 Elsevier Ltd. DOI: https://doi.org/10.1016/j.envsoft.2010.02.008
Tissot, C., Neethling, E., Rouan, M., Barbeau, G., Quénol, H. & Le Coq, C. (2017). Modeling Environmental Impacts on Viticultural Ecosystems. *International Journal of Agricultural and Environmental Information Systems*, vol. 8 (3), pp. 1–20. DOI: https://doi.org/10.4018/IJAEIS.2017070101
Valette, J., Amadieu, P. & Sentis, P. (2018). Cooperatives versus Corporations: Survival in the French Wine Industry. *Journal of Wine Economics*, vol. 13 (3), pp. 328–354. DOI: https://doi.org/10.1017/jwe.2017.1
van Leeuwen, C., Destrac-Irvine, A., Dubernet, M., Duchêne, E., Gowdy, M., Marguerit, E., Pieri, P., Parker, A., De Rességuier, L. & Ollat, N. (2019). An update on the impact of climate change in viticulture and potential adaptations. *Agronomy*, vol. 9 (9), pp. 1–20
van Leeuwen, C., Friant, P., Choné, X., Tregoat, O., Koundouras, S. & Dubourdieu, D. (2004). Influence of climate, soil, and cultivar on terroir. *American Journal of Enology and Viticulture*, vol. 55 (3), pp. 207–217
van Leeuwen, C. & Seguin, G. (2006). The concept of terroir in viticulture. *Journal of Wine Research*, vol. 17 (1), pp. 1–10. DOI:

https://doi.org/10.1080/09571260600633135
Wilensky, U. & Evanston, I. (1999). NetLogo: Center for connected learning and computer-based modeling. *Northwestern University, Evanston, Illinois, U.S.*, pp. 49–52
Wolkovich, E.M., García de Cortázar-Atauri, I., Morales-Castilla, I., Nicholas, K.A. & Lacombe, T. (2018). From Pinot to Xinomavro in the world's future wine-growing regions. *Nature Climate Change*, vol. 8 (1), pp. 29–37. DOI: https://doi.org/10.1038/s41558-017-0016-6
Zhu, X., Moriondo, M., van Ierland, E.C., Trombi, G. & Bindi, M. (2016). A model-based assessment of adaptation options for Chianti wine production in Tuscany (Italy) under climate change. *Regional Environmental Change*, vol. 16 (1), pp. 85–96 Springer Berlin Heidelberg. DOI: https://doi.org/10.1007/s10113-014-0622-z

Acknowledgements

First, I want to thank my supervisors Mark Brady and Maria Gerullis, for the help given in during the realisation of the model and in the writing of this document. A warm thank you to all my AFEPA friends at SLU and UBonn; it was a pleasant adventure despite covid. Finally, I am always grateful to my family for their support, love, and encouragement.

Appendix 1

A. ODD+D protocol

		Guiding questions	Description
I. Overview	I.i Purpose	I.i.a What is the purpose of the study?	We developed a theoretical agent-based model in which different institutional (i.e., voting mechanisms) and environmental (i.e., spatial heterogeneity) settings affect the interaction among wine geographical indication (GI) stakeholders through an endogenous institutional change process. Farms behave as a cooperative system and use a common GI label that grants higher returns. In the model, farm agents can endogenously change one common operational rule through voting. The rule they can amend is a production constraint (i.e., a quality standard). Wine quality is directly connected to climate, and climate change impacts farms' ability to respect the standard, use the GI label and achieve higher premia. The outcome of the endogenous institutional change process, therefore, could affect the system's climate resilience. The model allows testing different impact scenarios driven by two exogenous climate change processes and different institutional and environmental settings. As a theoretical model, it can be used to explore general system dynamics employing illustrative data representative of an average GI wine production system in the EU. Therefore, the aim is not to describe or predict any real-life setting. However, it might provide interesting theoretical insights on the role of institutional change in climate adaptation and resilience of agricultural production systems, contributing as a starting point for future research and model development.
		I.i.b For whom is the model designed?	The model is designed for researchers to contribute to future model development and study endogenous institutional change and its effects on climate resilience.
	I.ii Entities, state variables and scales	I.ii.a What kinds of entities are in the model?	• Human agents: **farms** • Institutional agent: **GI board** (representing a quality control and marketing collective agent).

			• Spatial units (grid-boxes of a regular square lattice)
		I.ii.b By what attributes (i.e. state variables and parameters) are these entities characterised?	**Global Variables:** PARAMETERS • "**minElevation**" and "**maxElevation**": Set to 0 and 800m. • "**minSoilQ**" and "**maxSoilQ**" [0, 1]. • "**avgGStemp**": Average growing season temperature. • "**optGStemp**": Optimal growing season temperature. • "**climateW**": Set to 0.6. Weight of microclimate in the definition of wine quality. • "**wineYield**" Set to 50 Hl/ha. • "**stdWinePrice**": Set to 1€. Standard wine price. • "**everyXyears**": Set to 5. How often the institutional change process is initiated (in years). • "**qualityDelta**": Set to 0.01 (i.e., 1%). The marginal change to the quality standard achievable in each institutional change process. • "**basBrandValue**": Minimum collective brand value affecting GI prestige. STATE VARIABLES • "**qualityStandard**": Initially set as minimum wine quality of all farms. • "**colBrandValue**": Collective brand values, a stock variable of the intangible capital the GI board invests in each year. • "**giPrestige**": A 0 - 4 scale integer variable affecting GI wine price. • "**giWinePrice**": Premium GI wine price increasing in levels with "giPrestige" (initially set at 1.5€). **Farms:** PARAMETERS (defined as globals but directly affecting farms' behaviour) • "**memory**": (Set to five). Defines how far farms can look into the past (in years) to make decisions in the institutional change process and the acquisition/abandonment of plots. • "**precision**": (Set to 2). Defines how sensitive farms are to perceive their own change in quality (e.g., 1 means they can notice a variation of 10% and 2 of 1%). • "**radius**": (Set to 3). An indicator of farms' mobility. It defines how far they can search in their neighbourhood to buy new plots. STATE VARIABLES • Location (x-y coordinates) • "**myPlots**": Farm's land endowment. • "**myQuality**": Farm's average quality. • "**capital**": Stock variable. • "**profit**": Each year's profit.

			• "**pastVintages**": List average quality of past vintages (memory). • "**pastProfits**": List of past profits (memory). • "**plantingRights**": Allow the farm to buy a new plot for viticulture. • "**ballot**": It expresses the farm's specific decision in the collective choice situation (institutional change process). **GI Board:** PARAMETERS (defined as globals but directly affecting GI board's behaviour) • "**%fee**": (Set to 0.1). Fixed percentage fee collected from farms revenues. • "**delta**": (Set to 0.5). Percentage of revenues invested in marketing to increase collective brand value. • "**rho**": (Set to 0.4). Intangible capital (collective brand value) depreciation rate. STATE VARIABLES • "**giRevenue**": Revenue generated by fees collected from farms. • "**mktExp**": Expenditure in marketing in year t (in euros). **Spatial units:** PARAMETERS • "**elevation**": in metres. • "**soilQ**": [0, 1]. Soil quality. • "**slope**" [0, 1]. Slope in %. • "**fixCost**": (Set to 2500 €/ha). Fixed cost of maintaining a plot. STATE VARIABLES • "**microclimate**": Average GS temperature of plot i in time t. • "**wineQ**" [0, 1]. Weighted function of soil quality and microclimate. • **"ageVines"**: Age of the vines. • "**fallow**": Boolean indicating if the plot is left fallow. • "**owner**": Plot's current owner. • "**pastOwners**": List of past owners of the plot. • "**varCost**": [2000, 20000] (€). Function of slope and related to labour costs per hectare. • "**prof**": Expected profit for the plot. • "**giLabel**": Boolean indicating if the quality standard is respected (i.e., plots' quality ≥ standard). • "**landPrice**": [0, 70000] (€). Function of quality and GI label.
		I.ii.c What are the exogenous factors / drivers of the model?	• **Climate change**: Two levels (+2°C and +3°C); • **Voting mechanisms**: Three levels (no-vote, absolute and relative majority). • **Landscape heterogeneity**:

			Two levels. (Heterogeneous - sigma = 1.5 and homogeneous - sigma = 3). Other parameters significantly affect the model dynamics but are kept constant (e.g., optimal GS temperature, quality delta, precision, and memory).
		I.ii.d If applicable, how is space included in the model?	Farms are located on a two-dimensional grid. Each grid cell corresponds to one hectare with different soil, altitude and slope. Spatial heterogeneity impacts final wine quality and production costs. Farms have limited mobility in finding new suitable plots.
		I.ii.e What are the temporal and spatial resolutions and extents of the model?	Yearly time steps, 50 years simulations. 100 x100 regular square lattice (10km x 10km), each grid cell representing 1 ha (100m x 100m).
	I.iii Process overview and scheduling	I.iii.a What entity does what, and in what order?	1. Environmental change: An external climate change process updates microclimate and wine quality in each grid cell. 2. Operational situation: a. Following simple heuristics, farms calculate their average quality and make decisions on land use (set unprofitable plots fallow), sell their wine output, and can buy or sell plots substituting low- with high-quality ones. b. The GI board reshape the GI area, assigning the GI label to plots that achieve the quality standard. Then, it collects a yearly fee from farmers, of which a fixed percentage is invested in marketing to increase the value of the collective brand. The collective brand value, together with quality and percentage of GI farms, determines the GI prestige which has an effect on the final GI wine price. Finally, the GI Board calculate the GI prestige and updates GI wine. 3. Collective Choice situation a. Each farm votes on how to change one common operational rule (quality standards). They vote based on the memory of their yield quality in the previous five years. b. Ballots are collected and the quality standard is changed depending on the voting mechanism in place. (See Appendix 1.D for a general flowchart of the model).
II. Design Concepts	II.i Theoretical and Empirical Background	II.i.a Which general concepts, theories or hypotheses are underlying the model's design at the system level or at the level(s) of the submodel(s)	We refer to Ostrom's Institutional Analysis and Development (IAD) framework (Ostrom 2009) with respect to the definition of institutions, rules and institutional change. The model dynamics are divided into two action situations as defined by Ostrom (i.e., an operational situation and a collective choice situation).

		(apart from the decision model)? What is the link to complexity and the purpose of the model?	The choice of climate change scenarios is inspired to IPCC (2018 sec. D). First, we consider a temperature increase by the end of the century, compared to preindustrial levels, of 2°C (high mitigation but still not enough to meet the Paris agreement). Then we also consider a 3°C increase corresponding to a slower more "cost-effective" mitigation scenario (i.e., a Business As Usual (BAU) scenario) as also agreed by Hausfather & Peters (2020). We merely consider the effect of the growing-season average temperature on grapes' ripening process, directly affecting sugar and acidity levels, which are important determinants of wine quality and also regulated in production standards. Ignoring specific soil and hydrological features of a region, it is possible to define an optimal temperature for the given variety in use (Jones *et al.* 2005; Ashenfelter & Storchmann 2016). We use this abstraction to represent how climate change could deteriorate the potential wine quality of a viticultural region, and we simplify further by considering quality as defined in a continuous [0, 1] interval. In our model, we assume that a region is entirely controlled by a single cooperative which is also responsible to manage the GI label. In this way, we simplify reality by assuming that no other collective agent (such as GI producers' consortial) are present, and each farm sells wine at the same price only dependent on whether it fulfils the GI quality standards. Thus, we focus on the complexity of the collective decision-making process (institutional change), and how environmental conditions (landscape heterogeneity) impact on individual and collective adaptive capacity. Finally, we draw on theoretical models and empirical research on collective reputation, collective brand value and intangible capital (Schamel 2009; Beckert *et al.* 2017; Fishman *et al.* 2018) to describe how the final GI wine price depends on the average quality achieved by the region, but also on the share of GI producers and the value invested in the collective brand (e.g., through advertising and other marketing activities).
		II.i.b On what assumptions is/are the agents' decision model(s) based?	In the operational situation, farms can act on land use decisions only. They face two different prices depending on whether their average quality is higher or lower than the quality standard. they adapt to environmental changes and try to maximise their profit by following a simple heuristic, i.e., they can leave plots fallow when no more profitable. On the other hand, farms have a memory of the quality and profits experienced in the last five years. If they notice a decrease in their average quality, they can sell their lowest quality plot, acquire a planting right, and purchase a

			higher quality plot nearby. They can also sell plots that were not profitable in the past and gradually abandon farming. No land market is implemented in this model (see submodels section). Moreover, it is assumed that farms always respect the quality standard and that the GI Board acts effectively in creating incentives to follow the rule (i.e., no moral hazard considered). The GI Board simply collects fees based on a fixed percentage of farms' revenues and invests a fixed share of the revenue in marketing to increase the value of the collective brand, which positively affects GI prestige and price. The rest of the budget is assumed to be allocated in quality control, ensuring farms respect the standards, and for other administrative expenses. Thus, this agent does not make decisions, but simply applies a fixed rule and updates global variables such as the collective brand value, GI wine price, and GI area. In the collective-choice situation (i.e., institutional change), only farms are involved, where they can vote to increase, decrease or keep the quality standard constant, depending on the quality of their past vintages. First, they are urged to decrease the standard if they cannot fulfil it in the present time, then they if perceive a decreasing trend in the previous five years they will also vote to decrease the standard. On the other hand, if the trend is increasing, and they can sustain a higher standard, farms will vote to increase it, and so on.
		II.i.c Why is /are certain decision model(s) chosen?	The decision model for farmers is a straightforward way of depicting profit maximisation and quality maximisation motives by controlling land-use decisions with a simple heuristic. However, sub-optimal decisions cannot be excluded (see submodels' section). The Institutional change process, and the GI Board's action, are based on examples from the wine sector and literature on cooperatives and consortia. We focused on the process of endogenous change of the quality standard, and therefore ignored the issue of quality control and moral hazard, by assuming that what the GI board spends on quality assurance is sufficient to ensure farms respect the standards at all times.
		II.i.d If the model/submodel (e.g. the decision model) is based on empirical data, where do the data come from?	Empirical data is only used to create a reasonable representation of a European wine GI region. Data on the average size, number of farms, and number of hectares of Europe's GI vineyards were taken from EUROSTAT and used for general model calibration. No empirical data is used to calibrate any parameter affecting model dynamics and agents' behaviour.

		II.i.e At which level of aggregation was the data available?	General country-specific data on EU GI viticulture is available for 2015.
	II.ii Individual Decision Making	II.ii.a What are the subjects and objects of the decision-making? On which level of aggregation is decision-making modelled? Are multiple levels of decision making included?	Farmers make decisions on two action situations sequentially and by using different heuristics. First, they adapt to environmental challenges and quality standards, by making land-use decisions, while trying to maximise profit and increase their quality in the (lower-level) operational situation. Then they participate in the process of endogenous institutional change by voting in the (higher-level) collective-choice situation. There, farms can increase, decrease, or keep constant the common quality standard. The GI Board does not make a real decision as discussed above.
		II.ii.b What is the basic rationality behind agent decision-making in the model? Do agents pursue an explicit objective or have other success criteria?	Farms do not maximise any objective function, they just try their best to adapt to climate change by letting the least profitable plots follow, sell lower quality, and buy higher quality land. In this way, they try to fulfil the quality standard which allows higher GI premia and thus higher profits.
		II.ii.c How do agents make their decisions?	Farms process information about past and present environmental variables and follow heuristics to adapt to environmental and institutional conditions. Moreover, farms use a simple heuristic, based on past experience to decide when to abandon farming and determine their vote in the collective-choice situation.
		II.ii.d Do the agents adapt their behaviour to changing endogenous and exogenous state variables? And if yes, how?	Every farm follows the same heuristic, both in operational and collective choice situations. However, in the first decision-making setting, farms have two possible strategies. Until the average quality of their plots is higher than the quality standard, they can pool grapes from different plots and produce only GI wine which commands a higher price. Otherwise, they will start selling wine from each plot separately, producing both high-quality GI wine and standard wine.
		II.ii.e Do social norms or cultural values play a role in the decision-making process?	No, social norms are not included in any form of incentive/payoff mechanisms or decision making process.
		II.ii.f Do spatial aspects play a role in the decision process?	Yes, a farm's location affects its behaviour and environmental challenges. No relocation of the farmstead is considered and farms have limited mobility in finding new suitable plots around them. Moreover, spatial heterogeneity impacts on an aggregate level on the institutional change process and therefore on collective decision making.

		II.ii.g Do temporal aspects play a role in the decision process?	Each year temperature increases following a linear trend. Agents have limited memory of the past which affects their behaviour at multiple levels. The quality standard can be changed over a fixed time frame of 5 years through collective action, and affects each agents' decisions.
		II.ii.h To which extent and how is uncertainty included in the agents' decision rules?	Uncertainty is not considered, temperature increases linearly each year degrading wine quality in a deterministic way. Evaluating their past experience farms predict that the same damaging climatic trend will apply in the future, making a correct but incomplete prediction.
	II.iii Learning	II.iii.a Is individual learning included in the decision process? How do individuals change their decision rules over time as consequence of their experience?	No.
		II.iii.b Is collective learning implemented in the model?	No.
	II.iv Individual Sensing	II.iv.a What endogenous and exogenous state variables are individuals assumed to sense and consider in their decisions? Is the sensing process erroneous?	As exogenous state variables, individuals sense the present wine quality of their plots and plots around them which guides their heuristic. They also have access to other environmental variables such as slope and elevation. They keep lists of past quality levels and profits (memory) that play an important role in both operational and collective choice situations. Finally, the quality standard is endogenously defined in the collective choice process and it impacts farms' decisions. The sensing process happens without systematic errors, but farms have a maximum precision in sensing wine quality and its variations over time (i.e., $\geq 1\%$ - to the 2nd decimal). Nonetheless, present wine quality is precisely calculated when confronted to the standard (i.e., to the 4th decimal).
		II.iv.b What state variables of which other individuals can an individual perceive? Is the sensing process erroneous?	The GI Board knows the average quality of all plots and farms revenues to the maximum level of precision.
		II.iv.c What is the spatial scale of sensing?	Global (GI Board), local (farms).
		II.iv.d Are the mechanisms by which agents obtain information modelled	All above-mentioned variables are just known by the agents.

		explicitly, or are individuals simply assumed to know these variables?	
		II.iv.e Are the costs for cognition and the costs for gathering information explicitly included in the model?	No.
	II.v Individual Prediction	II.v.a Which data do the agents use to predict future conditions?	Data on past average quality at the farm's level is used as a predictor of future quality, urging them to vote accordingly on the emendation of the quality standard or to start searching for new higher quality plots.
		II.v.b What internal models are agents assumed to use to estimate future conditions or consequences of their decisions?	Farms myopically estimate future environmental conditions, limited to understanding if their quality will deteriorate/improve due to climate change.
		II.v.c Might agents be erroneous in the prediction process, and how is it implemented?	Since the climate trend is deterministically modelled, by checking if, let's say, their quality was decreasing in the previous years, they correctly predict the same will continue in the future and try to adapt via land use and by pushing to decrease the quality standard. They access a list of previous quality levels and check if their average is lower than the present quality.
	II.vi Interaction	II.vi.a Are interactions among agents and entities assumed as direct or indirect?	Farms interact indirectly through voting on the quality standard. The GI board defines the GI area, important for individual farms decision making, and collects fees. Investing in collective brand value can limitedly substitute for quality, and keep higher premia, assuring farms economic viability.
		II.vi.b On what do the interactions depend?	Farms' interaction happens every 5 years (exogenously defined) and involves them all. On the contrary, the GI board act every year unconditionally after the farms in the operational arena.
		II.vi.c If the interactions involve communication, how are such communications represented?	No communication considered.
		II.vi.d If a coordination network exists, how does it affect the agent behaviour? Is the structure of the	No network considered.

		network imposed or emergent?	
	II.vii Collectives	II.vii.a Do the individuals form or belong to aggregations that affect and are affected by the individuals? Are these aggregations imposed by the modeller or do they emerge during the simulation?	No, except for the majorities/alignments emerging in the institutional change process (i.e., those who want to increase, decrease and keep the quality standard constant).
		II.vii.b How are collectives represented?	The GI Board represents a collective institutional agent, which acts for the common good of the system. However, it does it in autonomy from individual agents. Further, the way endogenous institutional change is modelled represents farms' collective adaptive decision-making process.
	II.viii Heterogeneity	II.viii.a Are the agents heterogeneous? If yes, which state variables and/or processes differ between the agents?	Farm size can vary. Moreover, due to heterogeneity in environmental variables, affecting variable costs and quality of plots, depending on their location farms have different average quality and total costs.
		II.viii.b Are the agents heterogeneous in their decision-making? If yes, which decision models or decision objects differ between the agents?	The agents are not heterogeneous in their decision-making.
	II.ix Stochasticity	II.ix.a What processes (including initialisation) are modelled by assuming they are random or partly random?	None, except for the environment initialisation (i.e., elevation and soil quality spatial pattern), the location of farms and their land endowment. However, farms are not located completely randomly (see submodel 1).
	II.x Observation	II.x.a What data are collected from the ABM for testing, understanding and analysing it, and how and when are they collected?	Data is collected at the end of each year, some variables are cumulated/counting other are flux variables. Economic/ production data: Average and total capital and profits of farms, number of farms (total, GI and standard wine farms), number of bankruptcies, total output (standard and GI wine). Average quality and quality standard, collective brand value. GI prestige and GI wine price.

			Institutional change data: Percentage GI area of total, quality standard, voting results (i.e., frequency of decrease, keep constant, increase), successful rule emendation. Environment variables: Number of fallow plots, ratio abandoned vs acquired plots.
		II.x.b What key results, outputs or characteristics of the model are emerging from the individuals? (Emergence)	The inclusion of endogenous institutional change led to considerable variations in all target variables, including the emergence of complex/chaotic behaviours. We showed how landscape heterogeneity has a twofold role in the climate resilience of the system. It increases individual adaptability but slows down collective adaptive capacity through institutional change. Considering absolute vs relative majority did not produce any relevant result. Institutional change results are sensitive to the memory parameter and extremely sensitive to the precision parameter.
III. Details	III.i Implementation Details	III.i.a. How has the model been implemented?	In the NetLogo platform (version 6.2), R and GIS extensions of the model are also implemented.
		III.i.b Is the model accessible, and if so where?	The code is available on the GitHub page of the Author.
	III.ii Initialisation	III.ii.a What is the initial state of the model world, i.e. at time t=0 of a simulation run?	A total of 680 farms located on a 100x100 lattice environment of which elevation is defined randomly from a uniform distribution (ranging from 0 to 800 m). This randomly generated raster is then smoothed with a gaussian kernel. The same applies to soil quality, which ranges from 0 to 1. A total of 1850 patches (hectares) are randomly assigned to the closest farm; this process ensures that the average farm size matches EU GI viticultural data (2.7 ha/farm). Farm initial capital allows them to cover total production costs for the first two years. The initial quality standard is set as the minimum of farms' average quality in time zero, reflecting the case in which each farm meets the standard. This defines which plot can attain the GI label and can sell wine at a higher price. Finally, the optimal GS temperature is exogenously set to match the average GS temperature of the region, meaning that the region has reached climatic optimality for the vine variety in use.
		III.ii.b Is the initialisation always the same, or is it allowed to vary among simulations?	Spatial heterogeneity is exogenously set. Two levels for the sigma (variance) of the Gaussian kernel are used to smooth altitude and soil quality. Heterogeneous environment (sigma = 1.5) homogeneous environment (sigma = 3). These two settings affect initialisation, even though the environment is randomly defined each time.

		III.ii.c Are the initial values chosen arbitrarily or based on data?	Some of the variables/parameters are based or calibrated on aggregated data of European GI viticulture, such as the number of farms, hectares, and average farm size. Others are informed guesses or adapted to the literature, such as average GS temperature, min and max elevation, “climateW", wine prices differences, “everyXyears”, “rho”. Other parameters are arbitrary, “optGStemp”, “radius”, “memory”, “precision”, “delta”, “%fee”, “qualityDelta”, “basBrandValue”.
	III.iii Input Data	III.iii.a Does the model use input from external sources such as data files or other models to represent processes that change over time?	NO.
	III.iv Submodels	III.iv.a What, in detail, are the submodels that represent the processes listed in ‘Process overview and scheduling’?	Environmental change (update patches’ temperature and quality) Farm heuristic: Set plots fallow, sell wine and update capital, sell low-quality plot, buy high-quality plot, abandon farming. GI Board action: Reshape the GI area, collect fees and invest marketing, update prestige and GI wine price. Institutional change
		III.iv.b What are the model parameters, their dimensions and reference values?	List of parameters in Appendix 1.C.
		III.iv.c How were the submodels designed or chosen, and how were they parameterised and then tested?	See Appendix 1.B.

B. Full submodels' description

Initialisation

A total of 680 farms is located on a 100x100 lattice environment of which elevation is defined randomly from a uniform distribution (ranging from 0 to 800 m). A random raster is generated and then smoothed with a gaussian kernel using an R program and the R extension in NetLogo. The Gaussian kernel is a 9x9 matrix with a sigma of 1.5 or 3, to attain a relatively heterogeneous or homogeneous landscape. The same technique is applied to generate a raster for soil quality, which ranges from 0 to 1. These rasters are used in the NetLogo programme to define the environment (i.e., world). Slope data is calculated by performing a convolution of the elevation data frame. This time a 3x3 kernel is applied modifying a code sample of the NetLogo GIS extension according to this slope algorithm). Once the elevation data is loaded, it is used to downscale an exogenously given average growing season (GS) temperature which value is set to 17°C which is a value seen in many viticultural regions (Jones *et al.* 2005). Downscaling simply follows the dry adiabatic lapse rate, for which temperature falls of 0.0098°C/m (9.8°C/km). Finally, the optimal GS temperature is exogenously set to match the average GS temperature of the region, meaning that the region has reached climatic optimality for the vine variety in use.

Average GS temperature and soil quality are then used to define the potential wine quality for each plot (i) using equation 1 (see Figure 6).

$$\mathrm{WineQ_i} = 0.4 \times \mathrm{SoilQ_i} + 0.6 \times \left(1 - \frac{(\mathrm{optGStemp} - \mathrm{GStemp_i})^2}{\mathrm{optGStemp}}\right) \qquad (1)$$

The choice of the weights reflects the hypothesis that microclimate is the most important component in the definition of wine *terroir* and quality together with the soil (van Leeuwen *et al.* 2004; van Leeuwen & Seguin 2006). The choice of the functional form, quadratic and perfectly concave, is inspired by results shown in Jones *et al.* (2005). This functional form is a plausible approximation of the relationship between wine quality and climate. Very close to the optimal temperature the quality variations are small, but dramatically increase then further it gets from the optimum up to a point in which the climate is not at all suitable to the grapevine variety in use. It is obviously a simplification, and different varieties can be more or less adaptable/susceptible to climate variation. The maximum wine quality (i.e., 1) is reached when a plot has the maximum soil quality of 1, and 0 percentage deviation from the optimal GS temperature.

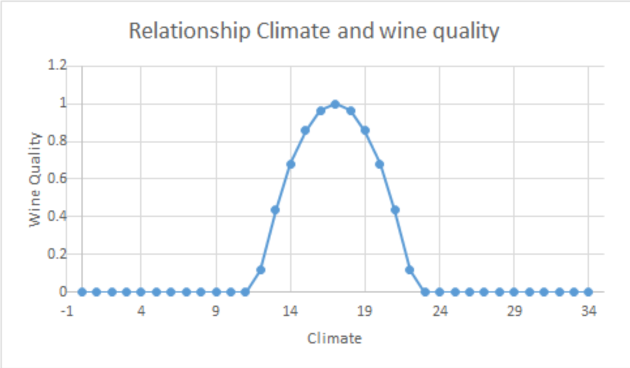


Figure 6. Wine quality given an optimal GS average temperature of 17°C and keeping a constant soil quality of 1.

Farms are not located totally randomly, to avoid collocation in unrealistic places. First, the plots with slope lower than 25% are selected, then 1850 patches with the best wine quality among the first selection are used to randomly locate the 680 farms, while ownership is assigned to the nearest farmstead. In this way, we represent the process of optimal adaptation of the viticultural area to the existing environmental conditions (which is part of the viticultural *terroir* concept), vines are a perennial crop, long term investments, and farms do not locate randomly. Moreover, in this way we also calibrate the model to match EUROSTAT data on number of farms, planted hectares and average farm size in GI systems. Farms initial capital allows them to cover production costs for the first two years. The quality standard is set as the minimum average wine quality of all farms, meaning that at period zero, they can all respect the standard. Two different prices are exogenously given in the initialisation: 1 €/l for standard wine (from plots with quality lower than the standard) and 1.5 €/l for GI wine. This price difference reflects consumers' WTP for an institutionally recognised label or general regional reputation as described in Schamel (2009) or Castriota (2020 chap. 6)**.** Also, wine yield is exogenously given to 5000 l/ha, a good proxy for quality GI in the EU.

The total cost per hectare is given by equation 2, where $FC_i = 2500€$ being the fixed costs for keeping the plot productive (including plots left fallow or with juvenile unproductive vines). Variable costs occur for production (applies to productive plots only) and are directly related to labour costs and plot's slope following Delay, Piou and Quenol (2015). Given the yearly salary of 20000€, a worker can harvest 10 ha if the slope is <=10%. Then, harvesting becomes increasingly difficult with slope, to the point where a worker can harvest only 1 ha if the slope is 100%. Slope takes values in the interval [0, 1]. In this way we skip modelling hiring labour, and use a continuous labour cost variable per hectare (e.g., a plot with slope 25% requires 0.25 farmers, thus 5000 €/ha*yr) (see Figure 7).

$$\mathrm{TC_i} = FC + \mathrm{slope_i} \times 20000 \quad (2)$$
$$\mathrm{prof_i} = 5000 \times \mathrm{p_w} - TC_i \quad (3)$$

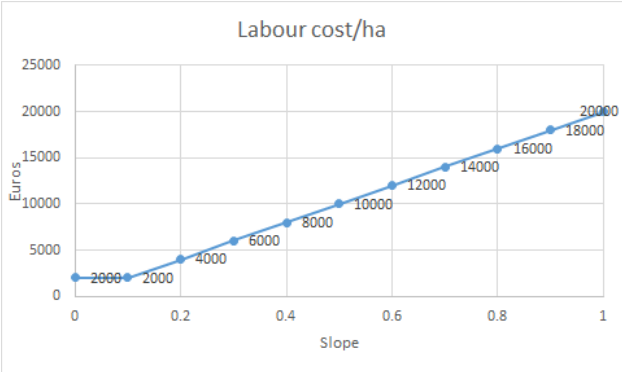


Figure 7. Variable (labour) cost per hectare increasing with slope (from 0.1 workers/ha to 1 worker/ha).

Given the prices and yield described above, if a farm sells standard wine (p_w= 1€), following the total revenue equation 3, it can barely cover the production costs of a plot with a relatively low slope of 12.5% (TC = TR = 5000 €/ha). With basic GI wine price this value increases to 25%. Finally, the land price is proportional to quality and is calculated following equation 4, with "giLabel" being a dummy variable. Official data on viticultural land prices is hard to find. Here we ponder a maximum price of 70000 €/ha.

$$P_i^{land} = \mathrm{wineQ_i} \times 50000 + \mathrm{giLabel_i} \times 20000 \quad (4)$$

Environmental change

A linear and deterministic climate change process raises the average GS temperature of each plot every year. Two climate change scenarios are considered: a more optimistic scenario, in which temperature increases of 0.0125°C/year and a more pessimistic one of 0.025°C/year. Since the global decadal average temperature has already increased by 1°C in 2020 compared to the pre-industrial level, supposed to start the model in 2020, the two trends would lead to a +2°C and +3°C global warming scenarios by the end of the century. These are in agreement with IPCC (2018), the first corresponding to a scenario with high emission reduction pledges, unfortunately still not in line with the Paris Agreement objectives, and the second a less ambitious (business as usual) mitigation scenario. After temperature, also wine quality is updated for each patch (equation 1).

Farm heuristic

Each year, all farms follow the same heuristic, which consists of the following five phases:

a. Set plots fallow

First, the farm calculates the average wine quality of each of its productive plots. Productive plots are the ones that are not fallow and that have vines older than three years. The farms adopt two different "strategies" depending on whether their average quality is greater-equal-less than the quality standard. When AVG. Quality ≥ Quality STD., they can pool all production and sell wine at the higher GI premium from every plot (i.e., pool strategy). In the opposite case, they can split production and sell both GI and standard wine separately from low- and high-quality plots (i.e., mixed strategy) (see figure 8). Leaving a plot fallow is the only way farms can avoid paying its production costs (i.e., variable labour costs).

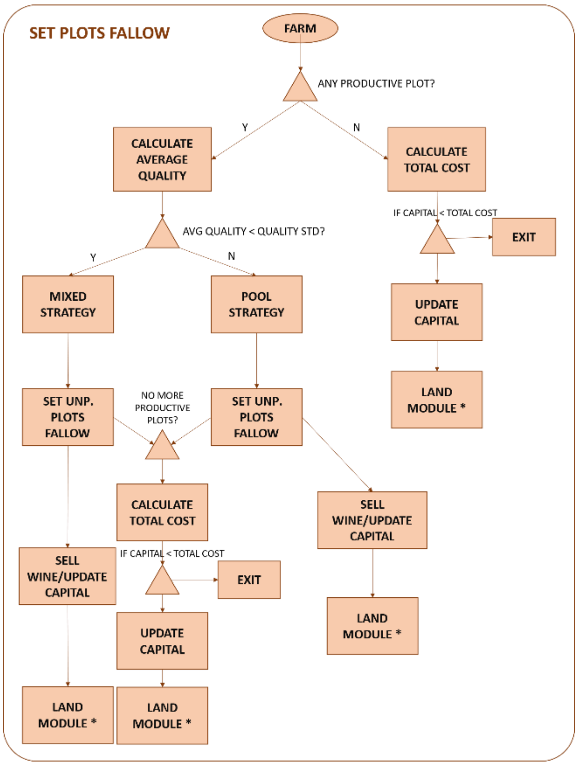


Figure 8. Flow chart of set plots follow heuristic.

In both strategies, if the expected profit of one plot is less than - 2500€ (i.e., fixed costs of keeping plot fallow) they will decide to set the plot fallow. Moreover, at the beginning of every year the farm checks if the quality level of fallow plots is higher than the standard to bring them back into production, which might happen to high elevation plots where temperature is too low at an early stage or when the quality standard is reduced. If the farm has no productive plots, they just update their capital by bearing the total costs (e.g., it happens when they plant new vines which are unproductive before they are productive, see phase d). This heuristic follows the logic of profit maximisation, even though sub-optimality cannot be excluded.

b. Sell wine and update capital

Farms collect their harvest, sell the wine to the respective prices and update their capital. This is to simplify the model since the vinification process takes time, and it is common for high-quality wine to be aged in barrels for two to three years. We also assume farms have no access to credit; thus, if they cannot cover production costs, they exit the business.

There is no real market for wine, all production is assumed to be sold at given prices. To conclude the module farms update vine age (see module d) and a list of past wine quality of the harvest and profits.

c. Sell plot

First it is important to clarify that no land market is modelled here, each plot is simply assumed to be free when no farm owns it, thus can be bought at the price defined by equation 4. On the other hand, plots that are no longer profitable or suitable, can be sold and simply become available to other purposes (no viticulture).

Farms can adopt a long-term adaptation measure and can buy one new higher quality plot per year. To do so, they must sell one of their plots and pull out the vines to attain a planting right. New vineyards' installations are strongly regulated in the EU and can reach a maximum of 1% of the total planted area each year (Pomarici and Sardone, 2020). To avoid dealing with the formation of a planting rights market, we assume that a new plot can only be cultivated if a farmer renounces another plot.

This strategy is applied when farms perceive their average quality has decreased over the previous five years (farm's memory) and a potential new plot is available nearby (radius of 3 patches). Then farms select the lowest quality plot, sell it, and eradicate the vines. They are also able to sense if the plot is downhill or uphill, selecting one with an elevation lower than the average value of their land. In this way, they avoid selling high elevation plots at early stages, keeping them as a "future asset". The farmstead plot is not included in this selection. Thus, an equilibrium is reached when the lowest quality plot at the lowest elevation is where the farmstead is located. In this case, the farm has no plot to sell and cannot acquire new ones.

d. Buy new plot

When farms sell a plot, or have a planting right from previous years, they can buy a new plot and plant vines on it. They search for a free and most profitable field (max $\pi > 0$) with quality higher than the quality standard in a radius of 3 patches from the farmstead. They also avoid plots which they already owned in the past, to avoid they continuously sell and buy the same plot. The vines' age is set to 0; they age each year after the farm sells wine and stay unproductive for three years. Juvenile vines still produce fixed costs of maintenance of 2500 €. The average vines' age in each plot does not get above 20 years. Despite being an arbitrary value, it means we assume that the vineyard is maintained at an optimal age level. Thus, we can ignore vines' life cycle and substitution of old vines.

In the end, capital and planting rights state variables are updated. Following points a, c and d, farms strive for a higher quality, trying to adapt to environmental conditions and keep up with the quality standard while maximising their profit.

e. Abandon farming

Finally, using a list of past profits, if farms have registered negative profits in the previous five years, they will sell the least profitable plot in the same way as in point c. When they have no other plot left than the farmstead plot, the farm agent perishes (i.e., farm exit).

GI Board action

a. Fees' collection and Marketing investment

First, the GI Board reshapes the GI area, checking which patches have quality higher than the quality standard and thus defining which patch gets the GI label (important information for farms heuristic since it defines plots profitability and land prices). It collects a fixed share (10%) of total farms' revenues. Half of the total GI board revenue is assumed to be spent to finance the process of quality controls, definition of the GI area and other administrative costs assumed exogenous. As we described earlier, there is no moral hazard in the model, and we assume that the GI board makes farms comply to the standard. The other half of the revenue is spent in an endogenous process of brand value creation. The Board invests in marketing ("mktExp") to increase the collective brand value ("CBV"), a form of intangible capital which behaves following a standard capital accumulation function (equation 5). The value of the collective brand depreciates fast, by 40% each year (ρ = 0.4), following literature on intangible capital (Corrado *et al.* 2020), therefore the system must produce high returns to increase this value. The GI board makes no profits (i.e., all revenues are invested in quality checks and marketing).

$$\mathrm{CBV}_t = \mathrm{CBV}_{t-1} + \mathrm{mktExp} - \rho * \mathrm{CBV}_{t-1} \tag{5}$$

b. GI prestige function

Finally, the Board updates the GI prestige level, which directly affects the final GI wine price. The GI prestige is a form of collective brand reputation, and it is represented by a five-level function depending on three variables: the collective brand value, average wine quality from productive GI plots, and the percentage of farms producing GI wine (i.e., farms that have at least one plot producing GI wine). These three variables are divided in five levels/intervals as Table 1 shows. Importantly, we set an arbitrary minimum value of collective brand value (named "basBrandValue" or "bbv") of 1000000 € to define the levels.

Table 1. (These tables are not numbered because already described in the main document)

	Level 0	Level 1	Level 2	Level 3	Level 4
GI quality	< 0.5	[0.5,0.7)	[0.7,0.8)	[0.8,0.9)	> 0.9
Collective brand value	< bbv	[bbv, 2*bbv)	[2*bbv, 3*bbv)	[3*bbv, 4*bbv)	> 4* bbv
% of GI farms	< 0.5	[0.5,0.7)	[0.7,0.8)	[0.8,0.9)	> 0.9

The average level of the three variables is rounded to the closest integer value and used as the GI prestige level. Increasing prestige level ensures a higher GI wine price as in Table 2. Level 0 corresponds to the standard wine price.

Table 2. (These tables are not numbered because already described in the main document)

GI prestige	Level 0	Level 1	Level 2	Level 3	Level 4
GI wine price	1	1.5	2	2.5	3

It is important to underline that the following framework is the result of modeller arbitrary choices. Both variables and the intervals set here have an important impact on the final outcome. The three variables affecting collective brand reputation (prestige) are inspired by theoretical literature of collective brand reputation and empirical studies on consumers willingness to pay (WTP) for wine. For Schamel (2009), the average quality of all producers in a region can be regarded as the collective reputation of that region, consumers will compare regional producers based on that information. He shows that the effect of region of origin on final wine price is a composition of regional brand and collective reputation value. We try to capture these two components by using the average quality of GI producers, and the collective brand value. Since we are in the experience goods domain, consumers will inform themselves on the prior average performance of the region to determine their WTP. For simplicity, we take only the most recent quality level into account (current year quality), even though an average value of past vintages might be more appropriate for future studies.

Differently from Schamel (2009), we are modelling a hypothetical region in which all producers are united under the same umbrella cooperative, and cannot invest in their own brands. Therefore, it makes sense to ignore the conflict between regional brand and individual brand reputation. Schamel shows that in regions with high quality, regional brands become less important compared to individual brands, which can be explained by a higher level of quality-based competition among producers.

Quality is important, but it is not the only element affecting consumers WTP. Beckert *et al.* (2017) demonstrate how other symbolic characteristics of wine can explain wine price differences (e.g., artistic components, *terroir*, regional history). All these characteristics are part of the symbolic capital of a region and can be communicated to the public by investing in marketing and advertising, capitalising in the collective brand value.

Finally, in a theoretical model, Fishman *et al.* (2018) show that in strict quality control collective brand settings, the number of producers can increase consumers' WTP, since they have more information (reducing uncertainty) about past quality compared to private brands. Following this logic increasing the share of GI producers in the region can have a positive effect on its prestige and final price.

The underlying idea is that a region can partially substitute average quality by consistently investing in other forms of intangible/symbolic capital embodied in the collective GI brand through marketing. Other than increasing total returns, the number of GI farms can also increase the signal provided to consumers. Other effects of production volume on price are not considered, even though they might be substantial. On the other hand, we also ignore any chance of product differentiation (e.g., creation of reserves and special selections).

Endogenous institutional change (collective-choice situation)

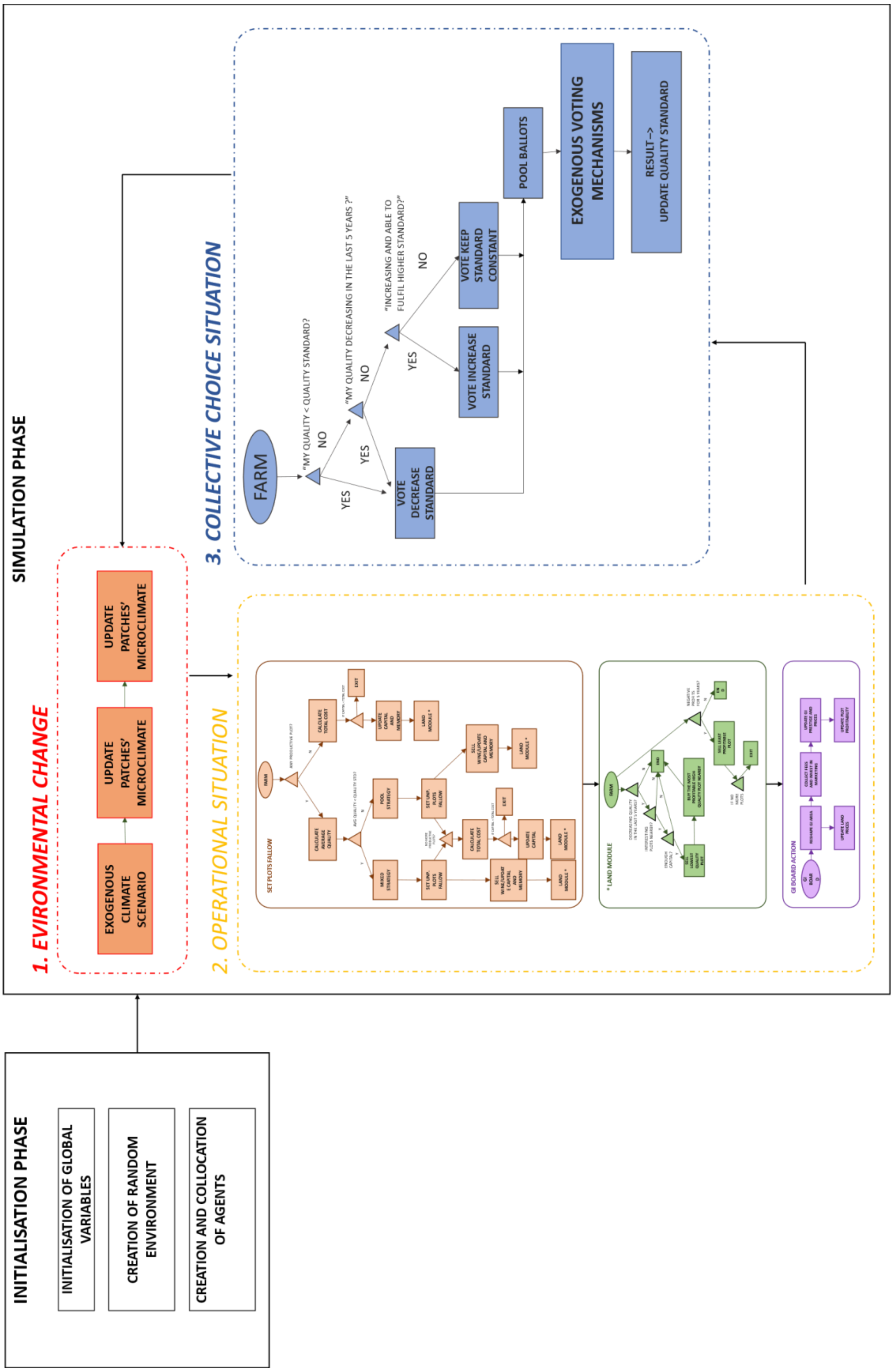
The quality standard can be endogenously amended by farms that can vote to keep it constant, increase, or decrease it. The delta variation achievable in each institutional change process is exogenously set to 1%. Institutional change is initiated every five years, a reasonable estimate for a long and centralised bureaucratic process. First, farms are urged to decrease the standard when they can no longer fulfil it in the current period. Then, they also check the average wine quality achieved in the previous five years (exogenously set memory). When their average quality is decreasing, they vote to lower the standard, while in the opposite case they vote to increase it only if they can still respect the higher standard. When no trend is shown in the previous years, farms will vote to keep the standard constant. Farms check trends by simply comparing the 5-year average quality with the present one. They can sense quality variations in the order of 1%, defined by the "prec" (precision) parameter through which quality variables are rounded. With the process described above, a farm-specific state variable called "ballot" is updated with value 1 (increase) -1 (decrease) or 0 (keep constant). Then ballots are collected on a list called "ballot-box". Votes are counted and then depending on the exogenously defined voting mechanism the final decision is taken. The ballot box is then emptied at the end of the process.

C. List of models' parameters[6]

"dimKernel" = 9
"maxSoilQ" = 1
"minSoilQ" = 0
"minElevation" = 0
"maxElevation" = 1000
"avgGStemp" = 17
"optGStemp" = 17
"climateW" = 0.6
"nFarms" = 680
"totArea" = 1850
"wineYield" = 5000
"stdWinePrice = 1"
"giWinePrice = 1.5"
"fixCost = 2500"
"radius" = 3
"memory" = 5
"prec" = 2
"everyXyears" = 5
"qualityDelta" = 0.01
"%fee" = 0.1
"delta" = 0.5
"rho" = 0.4
"basBrandValue" = 1000000

[6] See ODD + D protocol for description.

D. General flowchart of the model



Note: The aim or this figure it to provide an overview of the model flow with special attention on agents' heuristics in the operational and collective choice situations. It should not be taken as a complete accurate description of all program details.

Figure 9. General flowchart of the model with focus on agents' decision-making.

Appendix 2

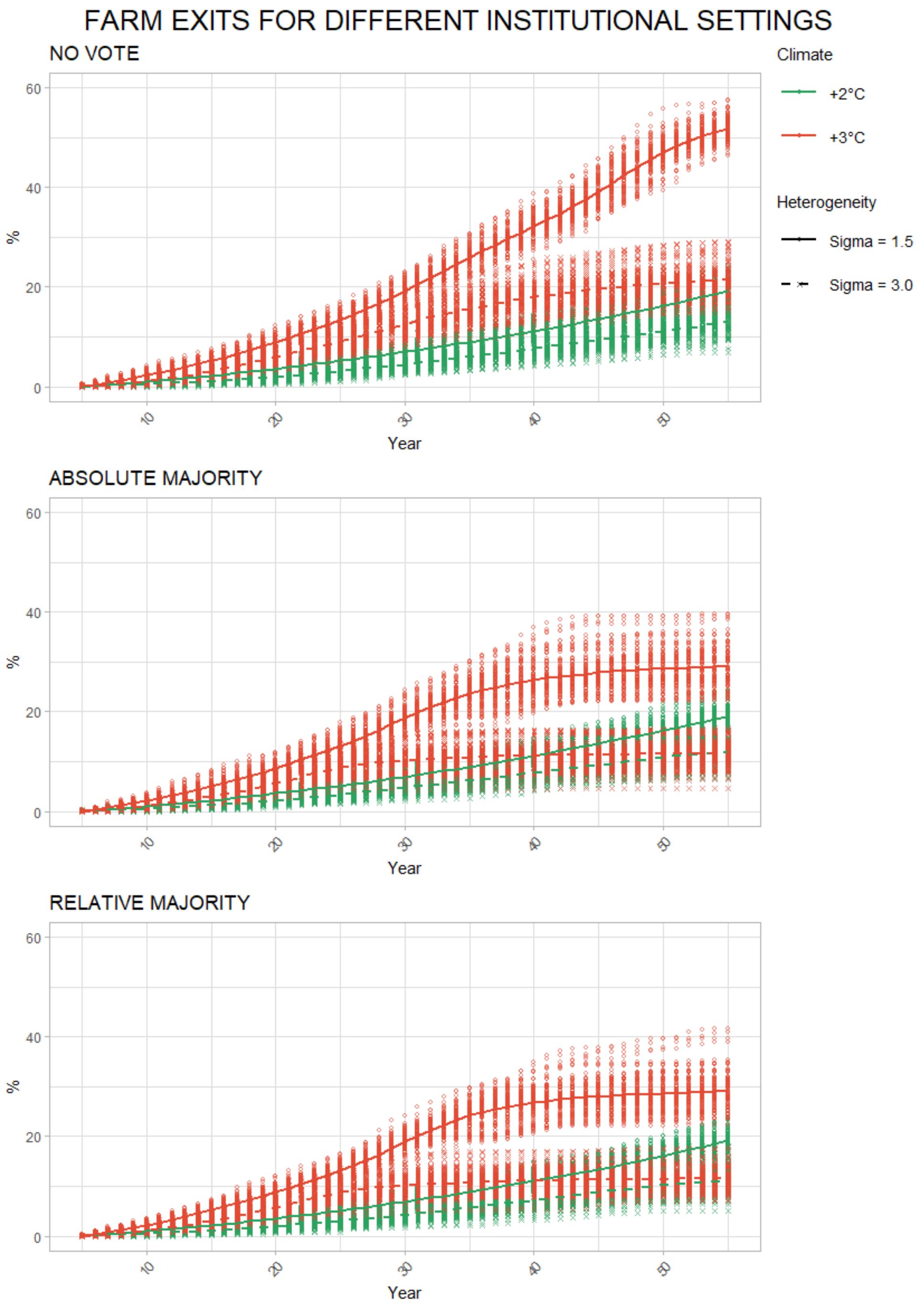


Figure 10. Farm Exits for different institutional settings.

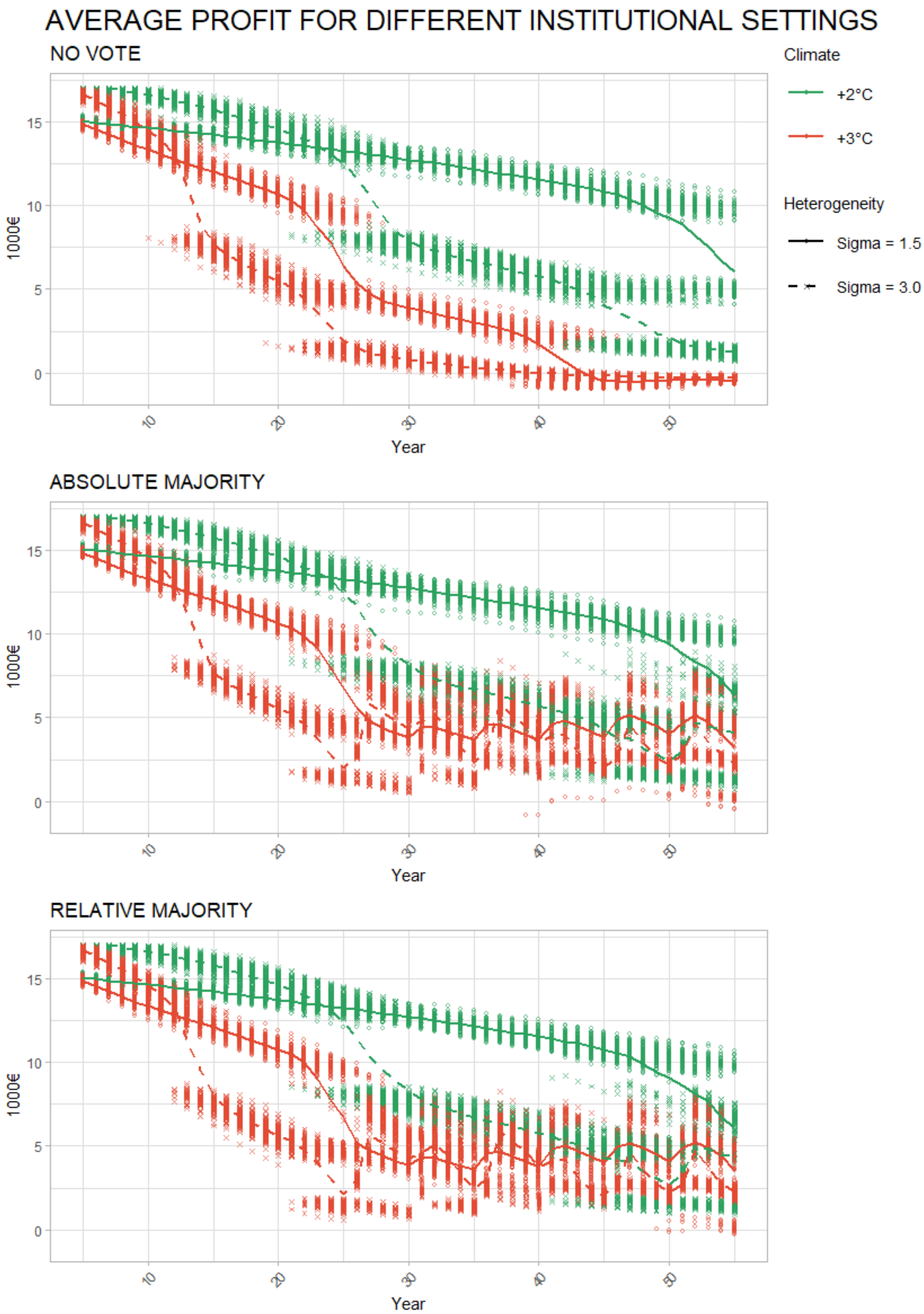


Figure 11. Average Profit for different institutional settings.

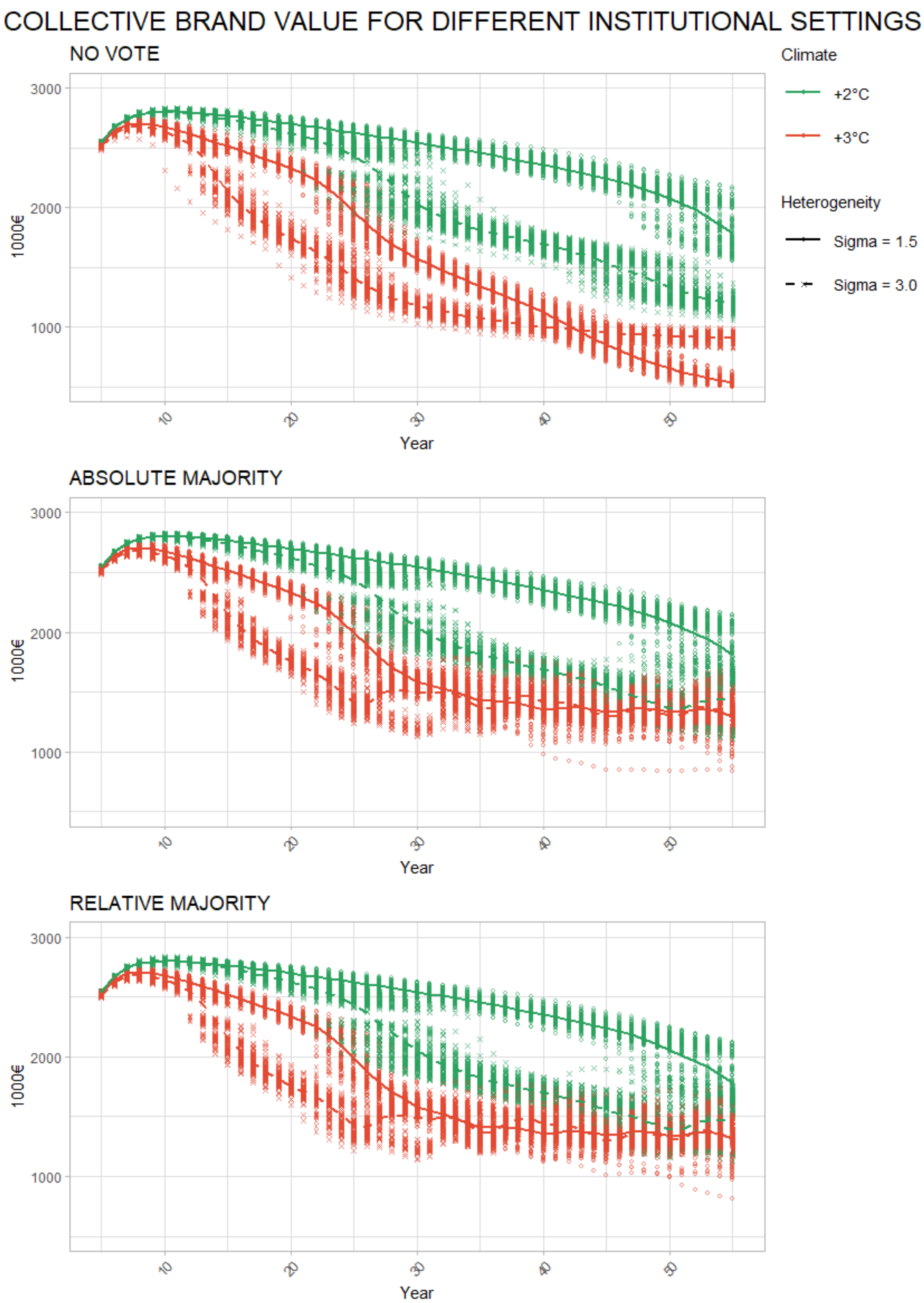


Figure 12. Collective Brand Value for different institutional settings.

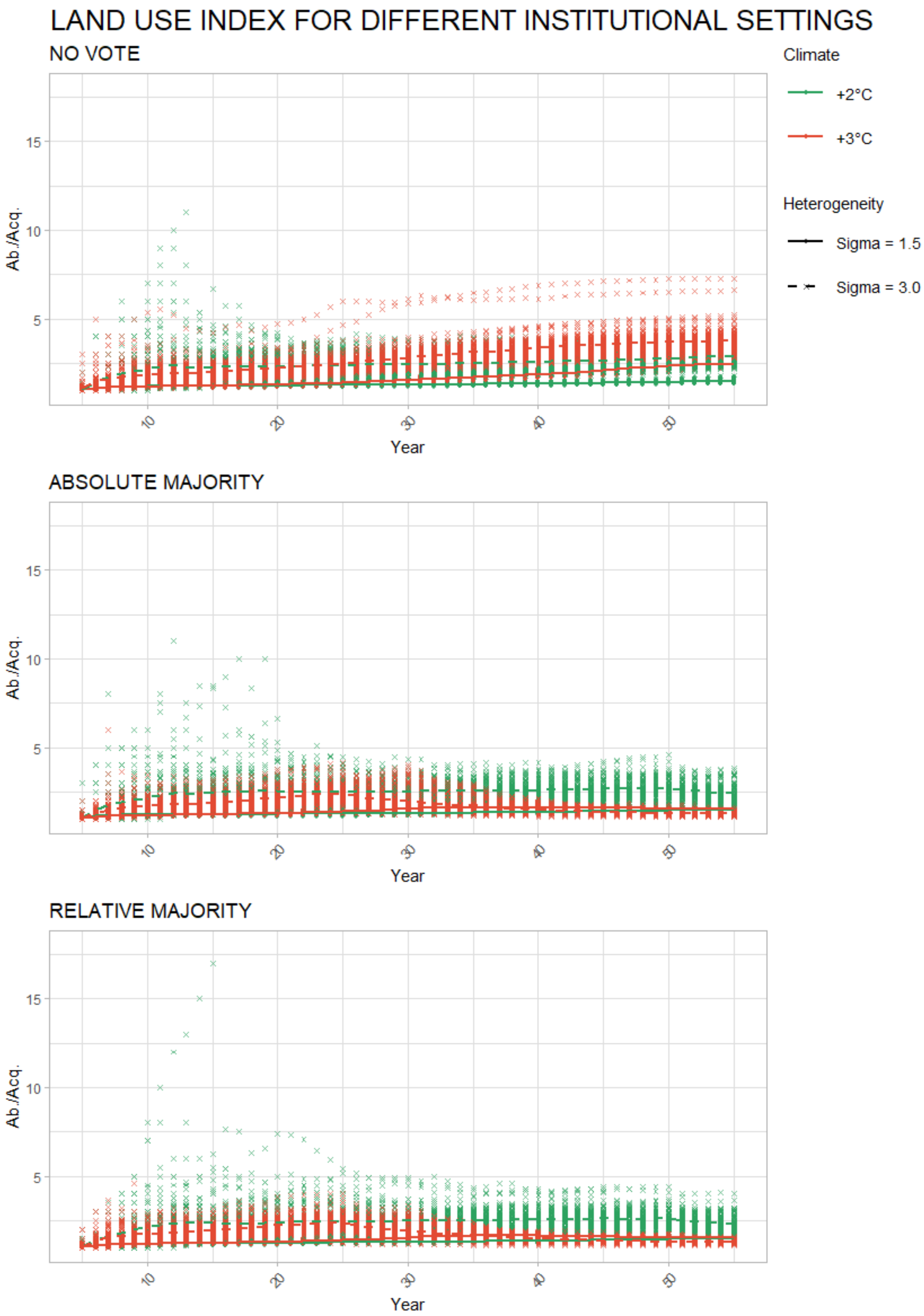


Figure 13. Land Use Index for different institutional settings.

Appendix 3

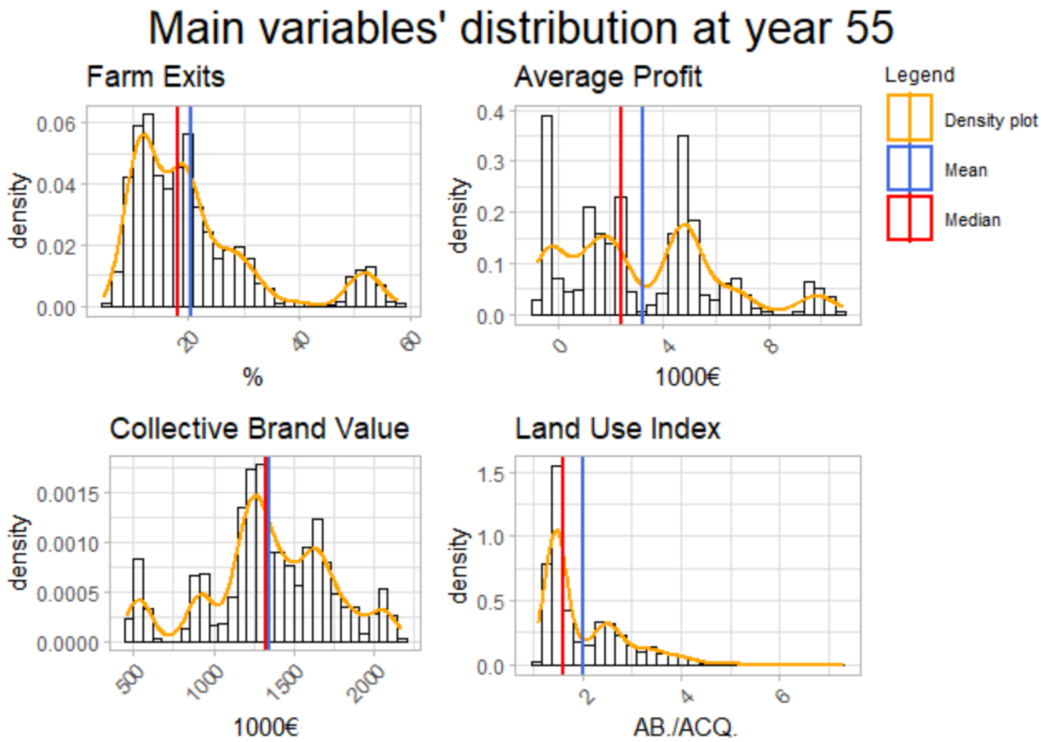


Figure 14. Distribution of main outcome variables at the end of the simulation (period 55).