OENO One
VINE AND WINE OPEN ACCESS JOURNAL
By IVES International Viticulture & Enology Society

DOI: https://doi.org/10.20870/oeno-one.2022.56.4.5557
OPEN ACCESS

ORIGINAL RESEARCH ARTICLE

Agrobiodiversity dynamics in a French wine-growing region

Antoine Doncieux[1], Olivier Yobrégat[2], Scott Prudham[1,3], Sophie Caillon[1♦] and Delphine Renard[1♦]

[1] CEFE, CNRS, Université de Montpellier, EPHE, IRD Montpellier, France
[2] Institut Français de la Vigne et du Vin, V'Innopôle Sud-Ouest, BP 22, 81310 Lisle-sur-Tarn, France
[3] Department of Geography and Planning, and School of the Environment, Uni
versity of Toronto, Toronto, Ontario, Canada

♦ authors share last authorship

ABSTRACT

Agrobiodiversity is a promising nature-based solution in the pursuit of sustainable agriculture. In wine-growing systems, commercial pressure and varietal regulations have narrowed agrobiodiversity in vineyards despite higher diversity being an important buffer against the effects of climate change. If drivers of grape diversity change are well-understood at national to global scales, little is known about the local, past or anticipated trajectories that drive agrobiodiversity dynamics depending on growers' cultural values, practices and choices. We combined quantitative agricultural census data and qualitative ethnographic approaches to characterise changes in the diversity of grape varieties from 1960 to 2020 at the communal and vineyard levels in a French wine-growing region, and to decipher the drivers of change. We highlight that vineyards have drastically changed in 60 years, with a decline in planted area and in farm number. We outline that despite a loss of varietal richness across both vineyard and communal scales, varietal richness remains high and evenness have increased across geographic scales in 2020. Ethnographic field observations emphasize that growers account for external drivers (e.g., market changes, regulation and policy, technology, environmental), but also cultural values when they choose which grape varieties to plant. Grape diversity was maintained despite market integration as an insurance to spread production risk, mitigate market volatility and address environmental uncertainties. Securing livelihoods in the midst of market changes has been a major concern for growers over the last six decades and remains so. Despite a pessimistic future vision of the vineyard shared by most growers, the Gaillac region has a cultural heritage that values diversity and that thereby supports adaptation to climate change. We expect that environmental factors may play a more important role in grape selection and planting sites in the future under the influence of climate change and pesticide reduction policies. In order to expand individual initiatives resulting in diversified grape selection, growers need to be better connected with stakeholders at a variety of institutional levels.

KEYWORDS: crop diversity, viticulture, cultural values, farmers local knowledge, cropping trajectory, Gaillac, ethnographic approach

*correspondence:
antoine.doncieux@cefe.cnrs.fr

Associate editor:
Vivian Zufferey

Received:
25 April 2022

Accepted:
25 October 2022

Published:
24 November 2022

INTRODUCTION

Agricultural systems with higher crop diversity compared to monocultures support higher wild biodiversity, provide multiple ecosystem services (Kremen and Miles, 2012; McDaniel *et al*., 2014) and are an important source of resilience to disturbances and the effects of climate change (Kremen and Miles, 2012; Renard and Tilman, 2019; Snapp *et al*., 2010). With the higher variability and unpredictability of climatic conditions, promoting crop diversity (hereafter agrobiodiversity) – from gene to species and from fields to landscapes – is a nature-based solution for reducing the risk of harvest and income losses while enhancing sustainability (Altieri *et al*., 2015; Lin, 2011; Renard and Tilman, 2019). In this context, reports of agrobiodiversity erosion is a major concern (Khoury *et al*., 2022). Although an alarming loss of 75 % of global agrobiodiversity since the 1900s has been reported (FAO, 2010), recent evaluations of trends in agrobiodiversity have shown contrasting results, mainly depending on the scale of analysis and choice of crop studied. Research has so far focused mostly on the main cereals (i.e., maize, rice, wheat, barley) and little is known about past changes in perennial crops, such as grapevines (Khoury *et al*., 2022). Because of their importance worldwide, changes in perennial cropping systems should also be assessed to improve the evaluation and understanding of the relationship between agrobiodiversity and agricultural resilience.

Grapevine is the world's third most valuable crop (Alston and Sambucci, 2019). During 8,000 years of domestication (Grassi and De Lorenzis, 2021; Maraš *et al*., 2020; Myles *et al*., 2011), diverse grapevine varieties (*Vitis vinifera* subsp. *vinifera*) have been selected and maintained by growers to fit local environmental conditions and to produce desired qualities in the crop (This *et al*., 2006). It is estimated that there are at present between 6,000 and 10,000 varieties of grapevine worldwide (Alleweldt and Possingham, 1988), of which 1,100 are solely grown for wine production (Wolkovich *et al*., 2018). Each variety is a distinct genotype associated with a unique mixture of taste, colour, yield and climate-related functional traits, such as phenology and water use efficiency (Schultz, 2003; Wolkovich *et al*., 2017). In addition to the *V. vinifera* varieties, interspecific hybrids are widely grown for cold and disease resistance (Bavaresco, 2019; De la Fuente Lloreda, 2018; Schneider *et al*., 2019). Despite the wide range of varieties in existence and their varying traits, 16 varieties account for half the world's planted area (as of 2016, see Anderson and Nelgen, 2020), and 12 or fewer varieties account for 70 - 90 % of vineyard area in many countries (Wolkovich *et al*., 2018). Low diversity is seen as a possible source of vulnerability in the face of experienced and projected changes in climatic conditions, and in turn, a potential threat to viticulture (see Santos *et al*., 2020 for a review; Morales-Castilla *et al*., 2020).

In a review of 232 case studies, Khoury et al. (2022) show that global drivers of agrobiodiversity changes over time are numerous, interrelated and place-dependent; they include market demands and global integration, urbanisation, demographic shifts, industrialisation and modernisation of agriculture (particularly mechanisation), commercialisation and transformation of farm inputs (e.g., commercially bred varieties), regulation and policy (including appellation rules governing prescribed and proscribed types of grapes), and climate change. The globalisation of markets and the popularisation of particular varieties are considered to be primary drivers of the narrowing of the diversity of crops in general and of grape diversity in particular (Anderson and Nelgen, 2021). Indeed, under the influence of the so-called New World model of winemaking and marketing, varietal wines such as Chardonnay, Sauvignon blanc, Pinot noir and Cabernet-Sauvignon have risen to the forefront since the 1980s, at the expense of varieties consumers may be less familiar with, or of blended wines whose varietal composition may be less apparent from labels and marketing (see e.g., Garcia-Parpet, 2008). Commercial pressures as well as national and regional varietal regulation through geographic indications also restrict growers to focusing on a handful of varieties (in general between 1-5 grape varieties in the French Appellation d'Origine Controlée system) that ostensibly match with their historical terroir (Van Leeuwen and Seguin, 2006).

If drivers of grape diversity decline are well-understood at national to global scales (Wolkovich *et al*., 2018), little is known about local and wine-growing regional trajectories, past or anticipated. At these larger scales, past studies have suggested that multiple factors can promote agrobiodiversity locally, including ecological or economic factors (e.g., organoleptic features, productivity, maturation time) and cultural values, such as aesthetic values, the pleasure of collecting and discovering new varieties and the social significance of the cultivar as a marker of cultural heritage (Brush *et al*., 1981; Elias *et al*., 2000; Heckler and Zent, 2008). Furthermore, the concept of terroir (particularly important in France) involves complex synergies between environmental (e.g., soil, climate, topography) and human factors, including cultural dimensions of wine-growing and winemaking practices that may be locally specific (e.g., vine training techniques) (Van Leeuwen and Seguin, 2006). Terroir is a highly charged concept in which local identity and commercial imperatives have led to protectionist measures based on unique geographical indications (Demossier, 2020) and which are tied to specific viticultural and vinicultural practices, often based on particular and limited grape varieties (Gade, 2004). However, no wine-growing region is static. Environmental, economic, regulatory and cultural factors all drive changes in grape varieties and the way the wine is made. This means that terroir should not be understood as a static concept (Anderson and Nelgen, 2022), and that capturing the holistic character of agrobiodiversity dynamics at the local scale needs to incorporate farmer knowledge and the specific influences on farmer choices (Berkes *et al*., 2000).

In this study, we combine quantitative agricultural census data with qualitative ethnographic approaches in order to describe

and analyse changes in the diversity of grape varieties planted at the vineyard to the communal scale between 1960 and 2020 in Gaillac, a French wine-growing region located in the Tarn department. Then, we deciphered the drivers of change and future expectation from the growers' point of view.

MATERIALS AND METHODS

1. Study area

The wine region of Gaillac is located in southwestern France in the Department of the Tarn (Figure 1). The total agricultural surface represents 51 % (i.e., ~ 300,000 ha) of the Tarn, of which 2.2 % (i.e., 6,541 ha) is occupied by grapevine (Data: Registre Parcellaire Graphique, 2017). Wine-growing takes place via 250 specialised farms, two vinicultural cooperatives and one wine merchant (Chambre d'Agriculture., 2020). In Gaillac, like in the South of France, (Béringuier, 1986; Touzard and Laporte, 1998), cooperative cellars have played a key role in the wine-growing system since the early 20th century (Rouvellac, 2008) and currently manage almost 50 % of the vineyard area.

The Gaillac region is home to seven Appellations d'Origine Contrôlées (AOCs) and two Indications Géographiques Protégées (IGPs) labels. Based on the concept of terroir and managed at the National level (by Institut National de l'Origine et de la Qualité, INAO*)* since 1935 (Humbert, 2011), AOCs and IGPs are the top two tiers in the French wine quality hierarchy; they certify that the grapes from which the labeled wine is made originate from a particular location, though the geographic scope of the label can vary widely from a few fields to – particularly where IGPs are concerned – entire regions. The labels also signify and recognise compliance with aspects of wine-growing (e.g., permitted varieties, maximum yields), winemaking, marketing and land use. The white wine AOC dates from 1938 and 1970 for reds and rosés. The AOC limits cover 72 *communes* (i.e., the lowest level of administrative division in France) and a total agricultural area of 71,786 ha, of which 8.9 % were under vine in 2017. The wine production is estimated at 400,000 hl per year with ~ 35 % of volumes produced in AOC, 45 % in IGP and 20 % in VSIG (Vin sans Indication Géographique) (average 1996–2016; IVSO, 2017).

Gaillac vineyards are a mixture of plains and hillsides (110–320 m). According to Riol (1913), four different terroirs have been identified from north to south: the plateau cordais, the premières côtes, the plaine du Tarn, the rive gauche terroirs (Figure 1). In addition to Riol (1913) mapping, Cunac terroir is located east of Albi and is not part of the white AOC. The climate is mainly dominated by oceanic influence, but subject to Mediterranean and continental ascendancies. Total yearly rainfall is 734 mm ± 125, and the mean annual temperature is 13.4 °C ± 0.59 (Data: Météo-France weather station of Albi, average 1990–2020).

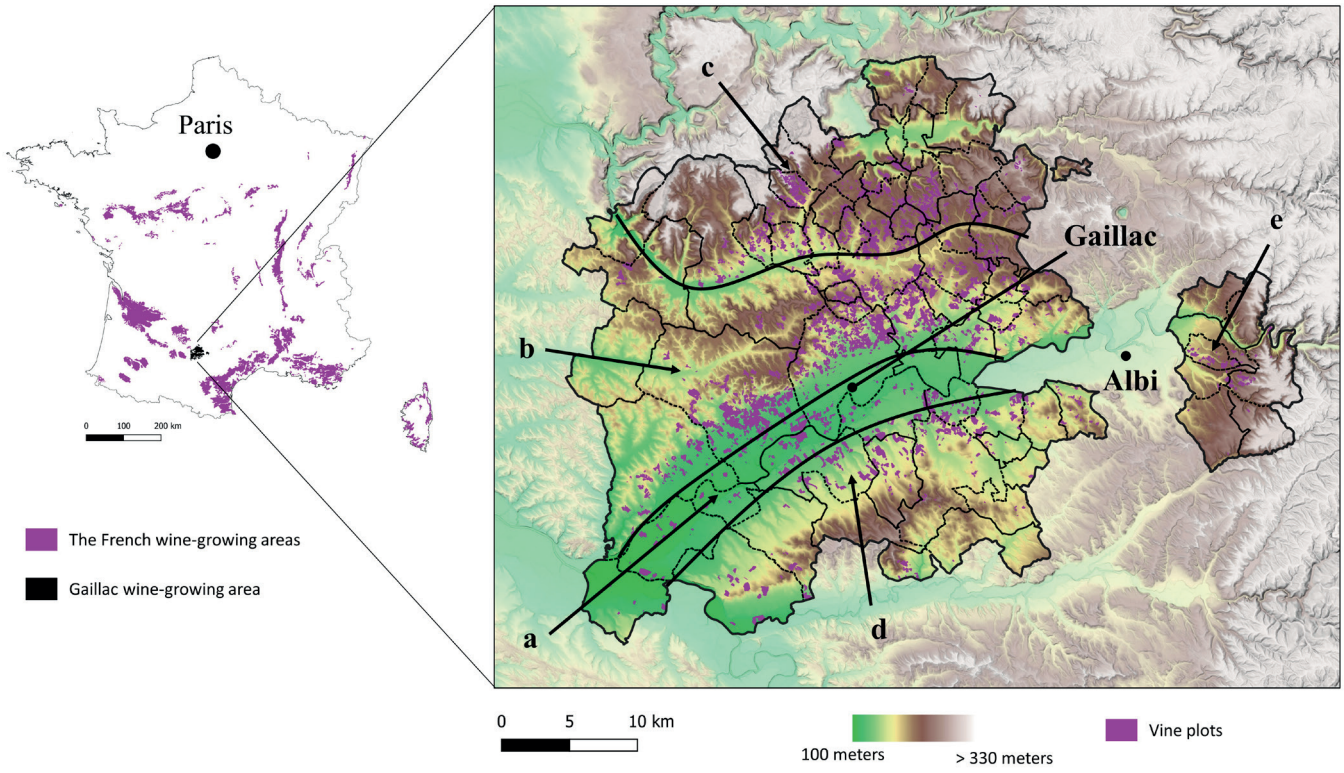

FIGURE 1. Location of the Gaillac wine-growing region.

The AOC delimitation of Gaillac is represented by bright colour, communes (N = 72) are delineated by a thin black line. The purple patterns represent the French wine-growing areas on the map of France and vine plots in Gaillac on the detailed map for the year 2021. The delimitation of the terroirs is represented with very thick lines: a) Plaine du Tarn (silty-sandy soils), b) Rive droite (carved out of clay-limestone hills), c) Plateau cordais (limestone plateau), d) *Rive gauche* (high stony and rolled pebbles), and e) Cunac (red clay soil with gravel) terroirs. Data vineyards: INAO (2021), CVI (2020) and IGN (2021).

A strong zonal temperature gradient between plain and hillsides leads to ± 10 days difference in harvest date (Delaunois *et al*., 1996).

Overall, there are 40 distinct grape varieties that can be used by growers to produce the AOC (14 varieties) or IGP (40 varieties) wines. Growers producing VSIG wines are not subject to any local regulatory constraints and can use the whole French national catalog of 324 wine grape varieties (FranceAgrimer, 2022). Some varieties, such as Len de l'el and Ondenc, are today only grown in Gaillac, and some, like Duras, were already being grown locally by the 15th century (Tallavignes, 1902). The diversity of grape varieties and long-term winemaking practices in combination with terroirs results in the production of a large diversity of wines (including sparkling, dry, sweet, liquorous, orange, reds and rosés).

2. Data collection

2.1. Historical grapevine inventories in the Gaillac AOC

We assessed the spatial and temporal changes in the diversity of grapevine varieties in our study area by using two censuses from 1960 and 2020. The two datasets provided data for all current 72 communes within the Gaillac AOC. The dataset from 1960 was originally carried out by the Institut des Vins de Consommation Courante (ICVV) between December 1956 and March 1959 at the scale of the Tarn. We accessed this dataset from INRAE Vassal-Montpellier Grapevine Biological Resources Center (Marseillan, France). The dataset provides the number and size of farms and total area under each grape variety held by grower at the communal level. Data for the year 2020 was provided by the Casier Viticole Informatisé (CVI), which is an exhaustive national database, as declared individually by each grower. The CVI provided the area planted and the name of grape varieties at the grower level. The variables common to both data sets were the number of farms, the surface area of the farms, the number and the area of grape varieties within all communes. We combined the two datasets using commune INSEE codes, the official geographic ID for listing communes in France. To ensure the comparability of the two databases, we checked whether the administrative boundaries of the communes did not change by georeferencing the 1960 cadastral map and compared it to the current communal division (OpenStreetMap) using QGIS (QGIS.org, 2022). We combined data for the four communes which merged and we used the 2020 commune boundaries as a reference for mapping.

2.2. Grapevine characteristics of Gaillac varieties

For each grapevine variety listed in our spatial-temporal dataset, we collected information about the use (e.g., as rootstock, table or wine grape production), berry colour, genetic identity (i.e., *Vitis vinifera* or hybrids) and phenology. We homogenised the variety names in the case of synonymy using the *Vitis* International Variety Catalogue (VICV). Berry colour was recorded for 188 grape varieties and genetic origin for the whole dataset. We defined international varieties according to the Robinson and Harding (2015) classification and local varieties using the Plageoles (2006) classification (see Supplementary Material for a detailed list). Data on variety phenology were collected from the Pl@ntgrape database, which includes the times of grape maturity (in weeks) as observed in the INRAE Domaine de Vassal Grape Collection. These times are provided using the Chasselas variety as a reference. On average, this variety reaches maturity (stage N on the Baggiolini scale) on 14th August (averaged over 50 years); i.e., on the 226th Day Of the Year (DOY). Syrah, for example, reaches maturity 2.5 weeks after Chasselas; therefore the time of maturity for this variety is expected on the 244th DOY. Finally, we classified the phenological times of the main grape varieties into three groups: early-season (≤ 237 DOY), mid-season (238–247 DOY) and late season (≥ 248 DOY). The phenological groups were built based on the local phenological classification used by the growers for harvest.

TABLE 1. Description of the historical documents reviewed. Numbers correspond with Table 3.

Titles	Authors	Dates	N°
Le vigneron gaillacois au contact des réalités et tourné vers l'avenir. Dossier vert, 1ère partie, vins blancs.	Bonnet, M.	1963	1
Le vignoble du Gaillacois. Mémoire de DES de Géographie.	Jalabert, J.	1967	2
Situation du vignoble en 1970	Department of Agriculture	1970	3
Le vignoble de Gaillac. Recueil des actes du millénaire de Gaillac 972-1972.	Cavaillé, A.	1975	4
Rapports d'études sur l'expérimentation de différents cépages et de clones dans le vignoble de Gaillac	ITV-SICAREX	1977	5
Schéma de restructuration du vignoble Tarnais	G.I.E des vignerons Gaillacois	1982	6
Diplôme National d'Œnologie : Suivis Œnologiques dans le Gaillacois	Berthezene-Garda, S. and Lurton, L.	1984	7
Enquête sur les structures des exploitations viticoles du Tarn	Rasse, E and G.I.E des vignerons Gaillacois	1987	8
Bilan de la restructuration du vignoble du Tarn (1982-2015)	IFV	2016	9
Développement d'une stratégie marketing collective pour les vins du Tarn	IVSO	2017	10
Cahier des charges de l'AOC Gaillac	Official Journal of the French Republic	1970–2019	11
Compte-rendu des réunions de conseil d'administration et d'assemblée générale (AOC et IGP)	AOC and IGP syndicates	1966–2020	12

2.3. Historical archives on the wine-growing system

In order to gather information on drivers of changes in grapevine diversity in the Gaillac winegrowing region, we consulted the municipal archives of Gaillac and those of the appellation's syndicate grouped in La Maison des Vins de Gaillac. Table 1 lists the documents reviewed ranging from 1963 to 2020. Historical sources included the AOC varietal legislation, AOC and IGP reports, agricultural advisor reports, surveys conducted by the AOC syndicate and an academic thesis.

2.4. Local knowledge on grapevine varieties

We used an ethnographic approach to document the knowledge of local growers on grape diversity dynamics over time. Field study was carried out over eight months (February 2020 to November 2021), including participant observation and semi-structured interviews. We used participant observation based on relations of trust to improve our understanding of the wine-growing activities in the area. Capturing words is not the only means of collecting data in social and human sciences; in addition to organising informal talks, in this approach we not only observed people's practices and actions, but also got actively involved by, for example, helping winegrowers to harvest or prune their vines. We preferred to be outside when addressing topics related to sense of place and the future trajectories of the vineyard; it is difficult to address these topics and concepts via formal interviews carried out inside, where visual cues are less accessible and references to the landscape, terroir and specific practices are more abstract.

In order to investigate grape diversity from an emic perspective (the grower's point of view), it is necessary to identify the grape variety. Indeed, growers often refer to a folk classification to distinguish between two different varieties according to phenotypic variations (e.g., berry colour), while genotyping using simple sequence repeat markers can show very low genetic distances and identical variety (Boursiquot and This, 1999). Our study was based on the Boursiquot and This (1999) definition of a variety: an array of clones resulting from the vegetative propagation of a single seedling. We thus transformed the varieties named by the growers into official names (e.g., Syrah for Sérine or Mauzac for Mauzac vert) using the VICV database.

The sampling strategy was developed to capture the heterogeneity of the grower populations. We interviewed 30 winegrowers (i.e., producers of both grapes and wines) and five vinegrowers (i.e., producers only of grapes which are sold to cooperative cellars or wine merchants). Both winegrowers and vinegrowers (hereafter all referred to as growers) were selected according to the number of grapevines varieties they grow, agricultural methods (conventional, organic and biodynamic), geographical localisation (across the four terroirs), seniority (number of years on the farm) and cultural inheritance (coming from a wine-growing family or not). Each grower cultivated from 3 to 18 (mean 10.4 ± 4.1) grape varieties. Our sample included 17 conventional and 18 organic and/or biodynamic farms, 17 growers came from the rive droite, eight from the rive gauche and ten from the plateau cordais. On average, the growers had been in charge of their farms for 23.5 ± 14 y/o. Lastly, 23 growers acquired their farms by inheritance and 12 are first generation growers.

The interviews were recorded (audio only) and they ran for two to four hours. The surveys consisted of mixed quantitative-qualitative questions and comprised three sections. The first section dealt with the history of the family and the farm, social information (e.g., date and place of birth, seniority in the farm) and professional background. The second section was a 20-minute discussion on issues related to grape vine diversity changes over time, drawing from maps of grape diversity changes between 1960 and 2020 that we had created using the data described in Section 2.1 (Supplementary Figures S1, S2 and S3). After the maps had been explained to the growers, they were asked to explain the background of wine-growing in 1960 and the past choice of grape varieties, and to give the main reasons for the changes in grape varieties over the last decades in Gaillac. Additional interviews were conducted with three retired winegrowers (mean age: 87 ± 2 y/o) to further explore the background of wine-growing during the second half of the 20th century with the help of maps. The final section of the interviews involved a series of open-ended questions regarding farm-level grape diversity. We sought to establish i) grower interest in cultivating multiple varieties, ii) whether they planned to uproot or plant new varieties in the following 10 years, and iii) how they foresaw the future of the vineyard over the next 30 years.

2.5. Ethical considerations

We clearly explained the purpose of the project to all participating individuals at the beginning of each interview. All the interviews were voluntary and non-remunerated. All the respondents remained anonymous and their answers were used strictly for the purpose of the study, and prior informed consent was obtained in writing. Our research project complies with the European General Data Protection Regulation (RGPD) on the protection of individual information under the reference 2-21088.

3. Data analyses

3.1. Quantitative analyses

All the statistical analyses was performed using R™ version 3.6.2 software (R Core Team, 2021). Statistical significance was set at $\alpha = 0.05$.

3.1.1. Wine-growing system at the vineyard scale

In order to obtain all data at the communal level for the two dates, we aggregated individual data from CVI (2020) at that scale. Then, the data were summed for the 72 communes (i.e., vineyard scale) for 1960 and 2020 separately to determine the total area under vine, the area of each variety and the total number of farms. We estimated the average farm size in 1960 by counting the number of farms in each area category provided in the database ("< 0.25 ha", "0.25 ha-0.99 ha", "1 ha-2.99 ha", "3ha-6.99 ha", "7 ha-14.99 ha","15 ha-29.99 ha, "> 30 ha") and by averaging the total area under vine for each farm in 2020.

The proportion of each attribute of grape variety (i.e., berry colours, genetic identity, international or local grape variety and phenological groups) at the vineyard scale was calculated by dividing the summed area of each type of grape variety by the total area under vine for 1960 and 2020. We compared the area represented by each phenological group for the main grape varieties in 1960 and 2020 using Pearson's chi-square tests. To characterise the phenological variation across the main cultivated grape varieties at the vineyard scale, we first calculated the average and standard deviation of the potential ripening period for 1960 and 2020 respectively. Then, we compared the mean potential maturation period between 1960 and 2020 using a non-parametric Wilcoxon test (package *stats* version 3.6.2; R Core Team, 2021), because the data did not follow a normal distribution according to the Shapiro-Wilk test ($W = 0.936$, $p < 0.05$).

3.1.2. Spatio-temporal dynamics in grapevine diversity within the Gaillac AOC

We first quantified the diversity of grapevine variety in each of the 72 communes of our study region for 1960 and 2020 separately, using multiple indexes widely used in ecology: varietal richness, Shannon's H diversity index (calculated using vegan R package (Oksanen *et al*., 2019)) and Pielou's J evenness index (Supplementary Equations (1) and (2)). The richness index is the number of grape varieties cultivated in a given commune. Shannon's H diversity index takes evenness and richness into account. The higher the value of H, the greater the number and evenness in the area planted in each grape variety in a given commune. A value of $H = 0$ would indicate a complete dominance of one grape variety in a commune. Pielou's J evenness index ranges from zero (indicating dominance) to one (indicating an equal abundance of all grape varieties). We compared the values of the three complementary diversity indexes between 1960 and 2020 with non-parametric Wilcoxon tests. For each commune, we then estimated how the composition of the set of grape varieties changed between 1960 and 2020 by computing a temporal beta-diversity index (TBI; Legendre, 2019) from the R package adespatial (Dray *et al*., 2021). We calculated the TBI index using a Bray-Curtis dissimilarity matrix (distance-based matrix) on grapevine area data (Legendre and De Cáceres, 2013). This index varies from zero (portfolios are exactly the same between the two dates) to one (portfolios have no shared varieties between the two dates).

3.2. Analyses of historical documents and growers' local knowledge

We first compiled the AOC varietal regulations framework from both 1960 to 2020. Historical documents were examined and relevant data were identified. We followed the guidelines provided by Olivier de Sardan (1995) to conduct and analyse individual interviews. First, the interviews were transcribed and analysed using the NVivo™ software (version release 1.5). Then, recurrent narratives from growers were identified, triangulated and described. The results are presented as both quotations and in summary narrative form and provide empirical evidence to support our arguments throughout the discussion. To maintain respondent anonymity, interview data are referenced by unique respondent numbers.

RESULTS AND DISCUSSION

1. Spatio-temporal dynamics of grape varietal diversity

Over the last 60 years, Gaillac vineyards have radically changed. In Gaillac, between 1960 and 2020, the wine-growing area decreased almost three-fold and the number of growers 22-fold; meanwhile, the average farm size increased six-fold (Table 2).

TABLE 2. Characteristics of Gaillac at wine-growing and communal scales for 1960 and 2020.

		1960	2020
Wine-growing scale	Area (ha)	17,522	6,545
	Number of farms	7,714	352
	Mean area of farms	< 3 ha	18.59 ± 22.14
	Total varietial richness	211	62
	Number of interspecific hybrids of *Vitis* sp	137	6
	Number of *Vitis vinifera*	74	56
	Area of hybrids (%)	22.5 %	0.2 %
	Area of international varieties (%)	0.04 %	32.6 %
	Area of local varieties (%)	39.6 %	46.6 %
	Mean potential ripening period	245th DOY ± 7.9 days	245th DOY ± 3.7 days
	Potential ripening period range	28 days	14 days
Communal level	Wine-growing rates (%)	13.8 ± 7.8	6.56 ± 6.96
	Mean varietial richness	33.9 ± 19.65	12.33 ± 7.73
	Mean H Shannon index	2.04 ± 0.53	1.98 ± 0.64
	Mean Pielou J evenness index	0.61 ± 0.11	0.84 ± 0.08
	Temporal beta-diversity index 1960–2020	0.93 ± 0.07	

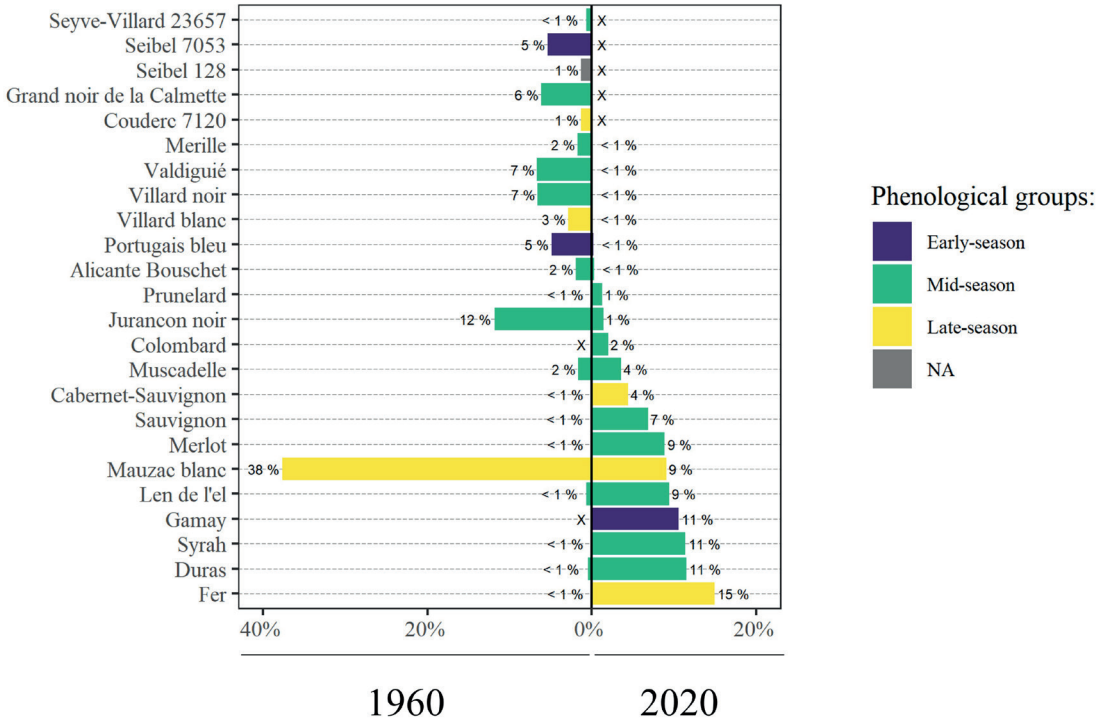

FIGURE 2. Grape varieties turnover between 1960 and 2020.

Main grape varieties cultivated in 1960 (N = 14 varieties, covering 92 % of total planted area) on the left side and 2020 (N = 13 varieties, covering 96 % of total wine-growing area) on the right side. Black crosses indicate that the variety was not cultivated and numbers represent the percentage of cultivated area. Barplot colours represent the ripening period of each variety: purple (early-season; < 237 DOY); green (mid-season (238–247); yellow (late-season; > 248 DOY) and grey (NA; missing values). Only the main grape varieties are represented for the sake of clarity.

We found that variety richness (Wilcoxon W = 4,524, $p < 0.001$) and evenness (Wilcoxon W = 185, $p < 0.001$) were both significantly different between 1960 and 2020, but we found a non-significant difference for the Shannon index (Wilcoxon W = 2,372, $p = 0.87$). A high TBIs index (0.93 ± 0.07) revealed that the portfolio of grape varieties was different between the two dates. In 1960, we inventoried 211 distinct grape varieties, including 74 *Vitis vinifera* cultivars (38 red varieties, 29 white and seven with undetermined colour) and 137 interspecific hybrids (77 red, 33 white, 5 varieties with another colour and 22 with undetermined colour). In the Gaillac region, hybrids occupied 22.5 % of the total wine-growing area at that time. Hybrids were originally developed in response to the phylloxera outbreak that devastated French vineyards at the end of the 19th century (Gale, 2011). In 2020, the total number of varieties had dropped to 62 varieties, including 56 *Vitis vinifera* and six hybrids. Overall, 174 grape varieties were discarded and the loss of diversity affected more red (61.6 % of abandonment) than white (31.79 % of abandonment) varieties. Loss of varietal richness was mainly due to the abandonment of hybrids which represented 77.6 % of total grape varietal losses. Hybrids were barely represented in terms of area (0.2 %) in 2020. While two varieties (Mauzac blanc for white varieties and Jurançon noir for red varieties) dominated the landscape in 1960, the distribution of the cultivated areas between the different grape varieties was more even in 2020 (Figure 2). The change in dominance was reflected by values of the Pielou index (Table 2).

Only 37 grape varieties were common to both dates, including two hybrid varieties (Villard blanc and Villard noir). Among these 37 varieties, the cultivated area has decreased for 20 varieties, on average by -79 % ± 29 %, and increased for 17 varieties, on average by 8,185 ± 28,410 % by a factor 0.2 to 118,000. Some varieties, such as the Valdiguié, have almost disappeared (area declined from 1,066 ha to 1.17 ha between 1960 and 2020) while other local varieties, like Mauzac blanc, have experienced a decline in area (from 6,006 ha to 594.7 ha), but still hold an important place in the vineyards. Overall, the area planted with both international and local grape varieties has increased significantly at vineyard scale over the last sixty years and occupied a 32.6 % and 46.6 % of the total surface area respectively by 2020 (Table 2). The local variety Fer (named "*Braucol*" in Gaillac) experienced the most important increase in area, from 0.02 ha in 1960 to 975.4 ha in 2020 (Figure 2).

Between 1960 and 2020, growers introduced 25 new varieties, including four disease resistant varieties (Artaban, Floreal, Souvignier gris and Vidoc) selected by research institutes, and varieties from other winegrowing regions in France (Gamay from the Beaujolais region, Chardonnay from Burgundy region) and from Spain (Mourvèdre). Among these introduced varieties, Gamay currently occupies the largest share of area (11 %).

Although non-significant (Wilcoxon W = 79.5; p = 0.95), changes in the portfolio of varieties induced a decrease in the range of the potential ripening period between the earliest and the latest grape varieties of two weeks between 1960 and 2020 (Table 2). We found a change in the proportion of grape varieties area within each phenological group over the 1960–2020 period (χ^2 = 6.22; p < 0.05). The proportion of early-season varieties (11 %) in the vineyard remained unchanged while growers cultivated more mid-season varieties (from 41.9 % to 59 %) and less late-season varieties (from 45.6 % to 29.8 %) in 2020 compared to 1960.

Over the 1960–2020 period, the communes located on the periphery (e.g., 62-Salvagnac, 61-Saint-Sulpice-La-Pointe, 36-Labessière-Candeil) of the vineyard were the most affected by vineyard area losses (loss from -70 to -99 %) and five communes (4-Arthès, 22-Combefa, 47-Mouzieys-Teulet, 58-Saint-Grégoire and 60-Saint-Marcel-Campes) experienced a total disappearance of wine-growing areas (Figure 3A[1,2]). The spatial distribution of grape diversity changed between 1960 and 2020 (Figure 3B[1,2], C[1,2] D[1,2]). In 1960, the NW vineyards were characterised by a low number of grape varieties with low evenness, and the SE communes had between two and three times more varieties, with a more even share of the area according to H and J indices (Figure 3B[1], C[1] D[1,]). The single commune of 53-Rabastens contained almost half (43 %) of total varietal richness in 1960 (i.e., 211 grape varieties).

In 2020, two communes (40-Lisle-sur-Tarn and 32-Gaillac) remained the hotspots of grape diversity (Figure 3 B[2]), holding more than half of the total varietal richness at the vineyard scale (37 and 33 grapes varieties respectively). Conversely, 25 communes grew less than ten distinct grape varieties. In addition, we observed a shift to red varieties in the communes where the Mauzac white variety was dominant -up to 76 % of the total planted areas for some communes like 10-Broze and 26-Donnazac in 1960.

2. Drivers of changes in grape varieties

Developing a good understanding of the drivers that influence grape diversity dynamics is essential for supporting sustainable agriculture (Labeyrie *et al*., 2021). The investigation of archives and interviews revealed six classes of drivers that could explain the trajectories (i.e., loss, maintenance and gain) of wine-growing activity and grape diversity in Gaillac (Table 3). We documented anthropogenic (changes in market, policies, land use, agricultural technologies and demography) and environmental drivers which can synergistically interact across times and spatial scales. A good example of such interaction is for the Portugais bleu variety; we documented that i) its commercial outlets selling it as a *vin médecin* for improving the previous year's wines had disappeared, ii) the wine quality was not in phase with the AOC policy and new consumer habits, and iii) the latter was due to its high sensitivity to diseases (i.e., downy and powdery mildews, acid rot and *Flavescence dorée*). Each driver is described and discussed in a dedicated section.

2.1. Market change

One grower explained that "*For the choice of grape varieties, it is the market that decides what growers plant […] because wine is not made for itself.*" (Grower 12). From local to global scales, changes in markets may be the most important driver of changes in crops in general (Labeyrie *et al*., 2021; Martin *et al*., 2019), and grapevines are no exception (Anderson and Nelgen, 2021; Moran, 1993). In particular, the internationalisation and even globalisation of the wine trade has propelled important changes in the wine sector, including the privileging of particular varieties, some of which have become global brands.

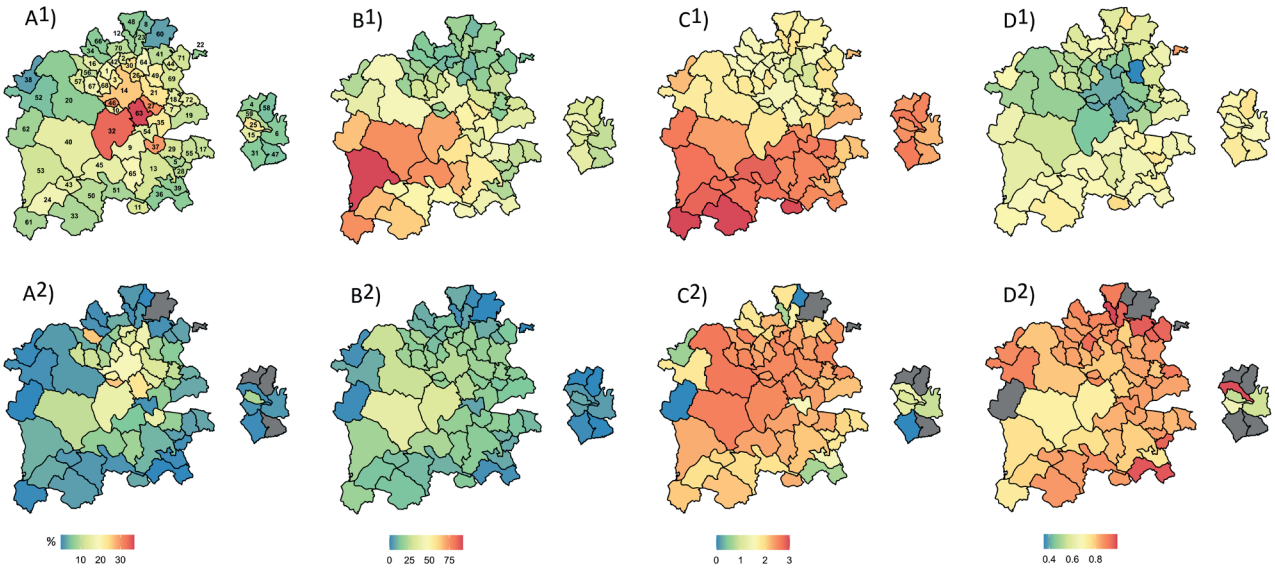

FIGURE 3. Communal-level diachronic maps (1960–2020) of the wine-growing system.

With A) percentage of communal area dedicated to wine-growing, B) varietal richness, C) H Shannon diversity index and D) J Pielou's evenness index for the 72 communes of Gaillac. The exponent 1 designates the map for 1960 and 2 for the 2020 maps. Numbers in the map A1 refer to the commune's location. A map locating all the different communes is published in Supplementary Figure S3.

TABLE 3. Documented drivers of change in grape diversity over 1960–2020 period.

Headings	Drivers of change	Examples	Change	Sources
Market change	Change in wine consumption	A model of occasional consumption with high quality wine replaced the traditional model of daily consumption	A, L	interview, 1, 3, 4, 6, 7, 8
	Globalization of market	Grape varieties commercial reputation	A, L	interview, 2, 7
	Demarcation from other growers	Grape varieties distinctiveness amid standardized market	A, L, M	interview
Policies	Varietal regulations	Incentive measures to force growers to focus on specific grape varieties via geographical indication	A, L, M	interview, 7, 11, 12
Land use	Urbanization	Reduction of the cultivation areas	L	interview
	Replacement by other crops	Withdrawal from wine-growing, shift to cereal production	L	interview, 2, 3, 4, 9
Agricultural technologies	Difficulty of mechanisation	Steep slope hillsides	L	interview
	Oenological technologies	Increase in wine quality via oenological analysis	M, A	interview
	Insitution and knowledge	Experimentation of clone, varieties-rootstocks association, organisation of journey in another wine-growing regions, dissemination of knowledge to growers via agriculturar advisors	A, L, M	interview, 5,7,8
	Pesticide use	The sensibility of the grape varieties to diseases is not an obstacle for grape variety selection	A, L	interview, 7
Demographic change	Decrease in the number of growers	No farm succession, withdrawal from wine-growing activities	L	interview, 2, 3, 4, 6, 7, 10
	Migration	Pieds-noirs immigration led to red varieties shift production and bring new winemaking practices	A	interview
Environnemental factors	Terroir suitability	Introduction of exotic grape varieties that match with soil types and local climate	A	interview, 1
	Desease outbreak	Disapperance of sensitive varieties to Flavescence dorée (e.g. Portugais Bleu)	L, A	interview
	Diversification	Grape diversity is used by growers as an insurance to overcome environmental and economic uncertainties	M, A	interview
	Climatic hazards	Repetitive late-frost spring events	L, A	interview,1, 2

Change: A = addition; M = maintenance; L = loss. Source: the method used to identify the drivers and the trend. Numbers are referring to historical documents listed in Table 1.

As from the middle of the 20th century, wine consumption has undergone some broad changes. In many countries, such as France, Spain and Italy, per capita wine consumption in 2016 was only one-third of peak 20th century levels (Anderson *et al*., 2017). In France, per capita consumption dropped after the 1960s, with a considerable decline in the demand for generic "*table wines*" (generally referred to as *vin de France*). Wine ceased to be the main drink, falling behind beer, soft drink or fruit juices, which are consumed by many young and urban people (Barber *et al*., 2008). This phenomenon is explained by profound changes in consumer lifestyle (e.g., driving, continuous days of work as opposed to coming home for a midday meal), and a general increase in income (Touzard and Laporte, 1998). Daily wine is abandoned in favour of the occasional "pleasure wine" of "superior quality" of labelled appellation. These changes in consumption have created a gap between production and consumer demands. In Gaillac, the gap was closed through changes in grape varieties and cultivated areas.

In 1982, in our study region, the vin de France was the dominant form of produced wine, with a volume of 1,163,845 hl and representing 85 % of total production, while the production of AOC and IGP wines represented 5 % and 10 % respectively of total production. The AOC and IGP wines were mainly made by the cooperative cellars: 56 % and 67 % respectively of total production (average 1976–1980). Wine production was still valorised as bulk for 90 % of winegrowers in 1986, and was primarily marketed by wine merchants who were more interested in the quantity than in the quality of the wine. During the 1960–1990 period, local wine merchants remained practically the only commercial outlet for growers. Following other European growers, the race for increased productivity was recognised as a dead end and growers began to shift toward grape varieties adapted to new wine consumer habits (Figure 2). European regulations contributed to causing this shift (see Section 2.2). Grape varieties that were too productive, that could not reach the appropriate sugar level and that did not meet the market criteria were discarded by growers.

Growers selected grape varieties during visits to a specific vineyard; they looked at the land or the overall economic status of the farm (i.e., Merlot from Bordeaux or Gamay from Beaujolais). Grower 36 illustrated this choice: "*At the end of the 1960s, I visited the Beaujolais region with a group of winegrowers. In a farm, in the yard, I saw two Mercedes [cars]. The winegrowers there looked richer, they were doing better. They had the Gamay, which seemed to make them money, then we brought the Gamay in our suitcases*". However, to stand out from other vineyards and assert their local identity, growers have also chosen grape varieties with legacy values grown before the phylloxera crisis, such as Fer, Duras or Len de l'el (Plageoles, 2006). Following a wine blending tradition, popular varieties were used to improve wine quality based on local varieties. For instance, Duras and Syrah are usually blended, Duras providing a peppery flavor and Syrah bringing tannins, colour and aromas.

Market expectations also differ depending on type of wine (i.e., AOC, IGP and VSIG), which is an important factor for growers to consider when selecting grape varieties. Although it is possible to produce IGP wines from AOC varieties, the latter is generally more restrictive (in multiple respects), and the growers reported the popularity and distinctiveness of grape varieties as being two characteristics that drive the market forces. As grower 10 explained: "*There are not a thousand questions to ask, if you want to make IGP wine, you take the international grape varieties that are easy to sell as long as people know the name of the grape variety on the bottle. A Chardonnay, nowadays, is sold easily […] If you want to make AOC wine, you grow local grape varieties, there is a market with story-telling. In Gaillac, growers do both AOC and IGP wine*." Consequently, international and local grape varieties coexist within the wine-growing system (Table 2). According to Wolkovich *et al*. (2018), the percentage of hectares in each region that is planted with international varieties varies across the globe, but is dominant in New World countries. For instance, international grape varieties represent more than 80 % of the planted hectares in China, Australia or New Zealand, because consumers clearly associate particular wine regions with specific and popular cultivars (Verdonk *et al*., 2015) (i.e. Syrah in Australia (Carew and Florkowski, 2008) or Chardonnay in California (Lima, 2006)). By contrast, the majority of wine-growing systems in Old World countries are based on local grape varieties, for instance Touriga nacional in Portugal, Airén in Spain, Rhoditis in Greece or Sangiovese in Italy (Andersen and Nelgen, 2020). Today, Gaillac is putting emphasis on local grape varieties in order to produce highly distinctive wines that stand out in a standardised wine market.

Over the last few decades, Gaillac has adopted a counterflow strategy in contrast to other French winegrowing regions that have often built their identity over the centuries on a single grape variety (Rouvellac, 2008). In the Gaillac region, the multiplicity of wines is produced from a multiplicity of terroirs and grape varieties. But grape diversification is also perceived as a disadvantage for some growers: "*The diversity of grape varieties dilutes the identity of the vineyard. The Cahors wine-growing region is associated with Malbec, the Bordeaux region with Merlot, but in Gaillac we do everything. This is an opportunity, but it is also pernicious. Consumers get lost with so much diversity, we are not identifiable on the market."* (Grower 36). According to the interviews, the Gaillac region is trying to expand in too many directions at once and suffers from an overall lack of visibility, while varietal specialisation has successfully underpinned the renowned products of most wine regions (e.g., Burgundy, Picpoul de Pinet).

2.2. Policies to replace grape varieties

Coercive policies, first through national and then through European regulations, was applied to address overproduction in France and to respond to the competition at the lower end of the market from Spain and Italy (Touzard and Laporte, 1998). These policies strongly limited the individual freedom of growers to plant the grape varieties of their choice.

Over the 1953-2008 period, grape varieties were officially listed in three categories (recommended, authorised and tolerated) depending on how adequate the grape variety was for the terroir (Galet, 1988) in each administrative subdivisions (e.g., *départements* in France). The specific varieties included in each category could be adjusted over time based on input from growers according to a prescribed process and some varieties were entirely discarded over time. Indeed, after restricting the use of tolerated varieties, which included hybrids, by cutting planting to 30 %, they were excluded altogether from the authorised list under penalty of punishment (Montaigne and Coelho, 2006), causing them to almost disappear in France in general (Reynier, 2012) and in Gaillac in particular (Table 2). Since 2008, a national catalogue has replaced the departmental classification and expanded the choice of varieties for growers of VSIG produce: from 60 varieties in the Tarn in 1982 to 324 in 2022.

European legislation has led to profound changes in wine-growing systems, in particular since 1976, through the implementation of regulatory measures such as the uprooting premium (designed to remove non-desirable varieties, as well as reduce the aggregate vineyard area) and planting rights regime (having permission to plant vines) (Avallone *et al*., 2018). Gaillac growers grubbed up vines and earned financial compensation for approximately 15,000 ha of hybrids and high-yielding varieties over the 1972–1992 period. From 1982 onwards, the wine-growing area dedicated to appellation-labelled production was collectively restructured, containing up to 5,713 ha of award-winning varieties between 1982 and 2016.

Within the framework of AOC regulation, the list of cultivable grape varieties has evolved over the last 60 years and has changed many times - up to nine times for red varieties (Supplementary Table S2). The AOC syndicate has also established a list of main and secondary grape varieties and guidelines for planted areas since the recognition of the red and rosé AOC in 1970. In 2022, for example, the proportion of main varieties (Fer, Duras, Syrah and Prunelard) grown in a farm must represent at least 70 % of total farm area

classified in AOC, while secondary varieties (Cabernet franc, Cabernet-Sauvignon, Gamay, Merlot) cannot exceed 30 % of the area on farms included in the AOC area. Such regulations are common in the Old World, and are particularly associated with geographical indication and terroir-based regulation (Meloni *et al*., 2019; Wolkovich *et al*., 2018), but they are, to our knowledge, not so common or quite rare in agrobiodiversity management in the rest of the world. Today, the spatial distribution of grape varieties in France (Supplementary Figure S4) is directly related to specific varietal regulations (Wolkovich *et al*., 2018) including as specified within the 363 AOPs and 74 IGPs which account for 93 % of total wine production (INAO, 2020).

Complying with the varietal regulations of the AOC standard "*[are] a freely chosen constraint*", as grower 7 conceded, but are also considered by growers as a complicated and rigid framework. As Cavaillé (1975) already pointed out, in Gaillac, the regulations are confusing for growers and the boundaries are blurred between what is mandatory and what is not, or what will soon become one or the other. Varietal regulations can also become a burden for growers who are forced to keep a particular variety which may not always be suited to their commercial outlets or to the local terroir in a changing climate. By controlling wine-growing, winemaking, marketing, land use and water management, geographical indications can be too rigid and thus render adaption to climate change more difficult (Meloni *et al*., 2019); however, the possibility of increasing flexibility is currently being studied in France (Aigrain *et al*., 2021).

2.3. Agricultural technologies and institutions

The choice of grape varieties made by growers has been influenced by the availability and affordability of new technologies, which have revolutionised agriculture over the past 60 years. As grower 34 noted: "*Since the generalisation of phytosanitary products, the sensitivity of grape varieties to diseases is not an obstacle for grape choice"*. According to Morton and Staub (2008), managing pest and fungal pathogen risks by applying chemical treatments are universal and ancient practices in wine-growing. In the 1960s, a new generation of fungicides was developed (e.g., benzimidazoles) characterised by low use rates, a broad spectrum and systemicity, which enabled extended spray intervals. These became very popular with growers. In turn, disease tolerant varieties, such as hybrids, lost their edge.

In the late 1970s, extensive research and experimentation have played a key role in the shift in grape varietal richness and evenness. Research aimed at breeding virus-free plants and identifying the best clones, variety-rootstock associations, pruning techniques and wine blending for a wide range of grape varieties, such as Duras, Syrah or Gamay. Local agricultural advisors have been largely responsible for the dissemination of this knowledge by following up with growers, leading wine tastings and organising study trips and on-farm experiments of grape varieties. For instance, the Fer variety is irregularly fertile and requires a long-pruning system like Guyot. Because growers were used to short goblet pruning, new knowledge brought by agricultural advisors on pruning was decisive in the adoption of Fer in Gaillac. Today, the local section of Institut Français de la Vigne et du Vin pursues trials of varieties to select good candidates for resisting and adapting to climate change.

Similarly to research institutions, cooperative cellars have instigated a change in the grapevine varieties used by their members. Since the middle of the 1960s, they have conducted experiments for the selection of grape varieties and participated in the multiplication and distribution of grafts. In 1965, to incite growers to plant specific varieties, they introduced differential payment which depended on the grape variety; for example, growers of hybrids were paid less than those of Jurançon noir and Mauzac, who in turn were paid less than growers of Gamay, Syrah or Duras. Today, differential payments are still in place for one cooperative cellar, and they apply to Sauvignon, Cot, Colombard and Gamay, which are paid 10 % more per weight than other varieties.

2.4. Demographic change

In the early 1960s, the independence of Algeria entailed a massive influx of French European-descent migrants ("Pieds-noirs*"*) to the Mediterranean area, including the Tarn department (Toujas-Pinède, 1965). As shown by Brun (1974), Pieds-noirs settlers caused profound changes in Mediterranean agricultural landscapes, like those in Corsica, the Var or Languedoc-Roussillon, by developing orchards, market gardens and vineyards. The Pieds-noirs farmers brought their knowledge and adopted agricultural innovations leading to profound changes to wine-growing systems in terms of grape varieties and the winemaking process. In Gaillac, most of them settled in the plateau cordais and rive droite. Historically, these were white-wine based terroirs, but the Pieds-noirs focused on the production of red grape varieties (e.g., Syrah and Merlot). Unlike most of the local growers, they i) did not rely on polyculture, ii) vinified the grape varieties separately, and iii) opted for indebtedness to build wine cellars and bought tractors. By producing more quality wines, some of Pieds-noirs farmers became a showcase for the vineyard and have been decisive in the recognition of the red appellation in 1970.

The sharp decline in the number of growers between 1960 and 2020 (Table 2) can be explained by the rural and agricultural exodus that occurred after Second World War. In the 1960s, "*everyone had vines. Whether it was the grocer or the baker. It was a way for them to save money."* (Grower 38), but the shift from one grower generation to the next led to a withdrawal from and consolidation of wine-growing. For instance, many growers preferred more stable job opportunities for their children, such as jobs in administration. In 1987, 60 % of growers were more than 50 years old and more than one grower in two (55 %) declared no planned farm succession. In addition, wine cellars were under-equipped and required important financial investments in order to produce quality wine. Thus, the growers who did not engage in the restructuring uprooted their vineyards

and several growers decided to shift their activity to cereal production, which is less strenuous and more profitable than winegrowing. The decrease in the number of farms has been accompanied by an expansion of farm area since the end of the 1980s, which has been accelerated by the European Union's Common Agricultural Policy (CAP) (Gray, 2000).

In addition, the proximity to Toulouse has boosted Gaillac demographically, accelerated by the construction of a regional motorway in 1992. Land competition between agriculture and urbanisation has significantly impacted the wine-growing areas, especially in the plaine du Tarn terroir, which follows the route of the motorway and remains a major concern for growers: "*In Gaillac, bare land is more expensive than land turned into vine. We are not a vineyard valued enough, like Pessac-Léognan or the Champagne region, which manage to have real estate projects cancelled. For example, vine plots of the communes of Saint-Sulpice and Rabastens are now supermarkets, residences or industrial areas*." (Grower 13). This local trend is part of a national phenomenon in France, where 2.5 million ha of agricultural land have been lost due to urbanisation during the 1960–2010 period (Bertrand and Bertrand, 2013).

2.5. Incidence of environmental factors

Environmental factors (e.g., climatic hazards and disease outbreak) have played a minor role in the grape turnover (Figure 2 and Table 2) compared to the other drivers we have discussed. In Gaillac, the varietal regulation choice described in Section 2.2 was not fully based on the optimal climatic conditions for varieties at the vineyard scale. In the 1970s, late-ripening grape varieties, such as Fer or Syrah, had difficulty in attaining ripeness, especially on the hillsides, and were often rotten before harvest because of the rains at the end of September. Their inclusion in the AOC register have given rise to numerous debates. To produce wines, winemaking techniques (e.g., chaptalisation or specific yeasts) and canopy management practices (e.g., leaf removal) were promoted to compensate for lack of sugar and aromatic compounds.

However, when events become impactful and repetitive enough to challenge the sustainability of the farm, growers change the grape varieties to ensure minimal harvest. Among climatic hazards, the winter frost wave of 1956 and multiple late-spring frosts (1957, 1963, 1974, 1980, 1981, 1991, 1997 and 2017) caused severe bud injury, resulting in very low grape yields and even trunk death. For instance, during the whole month of February in 1956, the temperatures dropped to between -10°C and -20°C, causing numerous damages to *Vitis vinifera*, in particular softwood varieties like Cot N, Portugais bleu and Négrette (Lavignac, 2001). The uprooted *Vitis vinifera* varieties were replaced by authorised hybrids, such as 7120 C or 13815 SV in the 1960s, in particular in the rive gauche and Plaine du Tarn terroirs:

"*After repetitive frost events, my father and other farmers planted hybrids because they didn't need rootstocks, they were productive and they were resistant to diseases. Especially, hybrids could re-fruit again after frost events, ensuring a minimal harvest. They were the only grape varieties to have produced grape during the 1956 harvest.*" (Grower 5).

Because year-to-year climate is variable under the influence of oceanic, Mediterranean and continental ascendancies, growers cannot anticipate which variety will grow best. To benefit from annual environmental features and to avoid crop failure, on-farm growers rely on different grape genotypes which exhibit different responses to environmental stresses to spread production risks:

"*The climate here is 70 % oceanic and 30 % Mediterranean with more or less windy years […] In wet years, the early-season varieties do best, because the late-season varieties do not ripen and can rot. In warm years, the late-season varieties ripen […] When one variety fails due to bad flowering process, others varieties offset production.*" (Grower 7)

Moreover, growing a rich portfolio increases the possibilities of wine blending by taking advantage of the organoleptic diversity of the grape varieties, which are useful for mitigating a bad year. For instance, in cold years, Merlot is used for increasing the sugar content of late-season Fer without the need for chaptalisation. Finally, a rich portfolio is also handy for dealing with wine market evolution by offering a wide range of products to consumers. As it is the case in many traditional farming societies, this diversity is used by growers as an insurance to overcome environmental and economic uncertainties (Jarvis *et al*., 2008; Lin, 2011) - a mechanism analogous to those underpinning resilience in natural ecosystems (Loreau and de Mazancourt, 2008; Tilman *et al*., 1996; Yachi and Loreau, 1999).

3. Cultural values to support varietal richness and evenness

The drivers described above cannot fully account for the changes in grape diversity we observed in Gaillac. Ethnographic field work showed that cultural values, such as entertainment, experimentation with or habituation to varieties, contribute to explaining local agrobiodiversity dynamics.

During discussions, growers expressed their total commitment to growing several exigent varieties that require special attention in the field and in the winery cellar. As grower 2 related: *"I would be very bored in Sancerre or Burgundy if I had to grow and vinify only one or two grape varieties"*.

Our ethnographic approach show that some growers are continually on the lookout for alternative varieties and expressed a strong feeling about the importance of experimentation with new grape varieties in the area: "*The different grape varieties do not give the same thing depending on their region of origin. If we plant it, we can talk about it […] And we'll see if it will adapt to the soil, the climate, the environment and so on.*" (Grower 19). As shown by Rouvellac (2008), growers in Gaillac are looking for in-depth knowledge about relationships between grape varieties and terroirs to produce quality wine. In practice, some growers use small plots of land and they observe and evaluate results over a certain number of years in order to determine whether

their experiment meets their goals and expectations. If the trial is considered a success in terms of agronomic and wine qualities, the grower may decide to plant additional plots of these grape varieties. Knowledge gained from the experiment can then be passed on to other growers, impacting grape variety evenness at vineyard scale.

By contrast, knowledge gained through long-term history with specific grape varieties fosters trust and confidence in the variety and that it has the desired characteristics and qualities in relation to the terroirs. Grower habituation can lead to them maintaining the use of specific grape varieties and a reluctance to adopting new ones. For instance, the hybrids Jurançon noir and Portugais bleu were widely used by the growers and "*had the trust of the growers, who were attached to them*", as noted by grower 38. In the 1970s, growers were suspicious of novelty and only acted when they had been convinced by virtue of what they saw and by what paid off: *"Growers were reluctant to plant the Fer variety, because they were used to other varieties, they did not believe in a legend that everyone was talking about and nobody had seen. Fer was unknown and had an irregular production reputation for people. They waited to see before acting."* (Grower 37). As shown by Nicholas and Durham (2012) in California, growers tends to rely on their own experience to guide their management decisions. Thus, long experience with a certain suite of varieties can lead to a reluctance by growers to change their grape portfolio, in the absence of new and direct experience with alternatives (Kenny and Harrison, 1992).

Further interviews to explore individual motivations may reveal more cultural values associated with grape varieties, such as patrimonial values (Blonde *et al*., 2016). Our interviews strongly suggested that cultural values, such as attachment-to-place/terroir and family/terroir legacy, are key factors that have been long underestimated and require further research. Such cultural values are also true for other crops; for taro (*Colocasia esculenta* (L.) Schot) in Vanuatu, Caillon (2005) showed that motivations differed between the most common and the rarest varieties, which are associated with cultural and family heritage and memory values. Similar results can be expected for viticulture considering the longterm relationship that develops between grower and plant over the generations.

4. Expected trajectories of the Gaillac wine-growing system

According to the interviews, the respondents share a pessimistic vision of the future of the Gaillac winegrowing area: between a quarter and a half of the wine-growing surface area could disappear in the next 30 years if European institutions were to grant uprooting premiums. This finding is supported by a combination of factors currently impacting the wine-growing sector. More than one grower out of two (55 %) is over 55 years old and the majority of them no longer have a succession plan (IVSO, 2017). Despite the attractive price per hectare of land (10,500 €/ha), non-family facilities remain few and these have difficulty in accessing land with agricultural buildings, such as wine cellars, which are often not sold by retiring growers. Wine-growing – and more broadly agriculture (Pawlak *et al*., 2021) – suffers from a lack of attractiveness. This is exacerbated in a context of declining wine sales and public policies aimed at reducing alcohol consumption (Spach, 2016).

Facing doubts about the viability of wine-growing and the demographic future of the region, the vast majority of growers are caught up in the short term and have insufficient time to anticipate and plan adequately for the future. In Gaillac, the AOC appellations are not highly valued in comparison to other French AOCs, which means that considerable time and energy is put into wine selling, relegating other tasks and issues to the background. The growers emphasise that the collective momentum generated since the 1980s with the restructuring of the vineyard has stalled, and that they are currently moving forward individually.

Farms that cannot guarantee their own sustainability are faced with an uncertain future and they anticipate few changes in farm management within the next 30 years: "*I am retiring in five years and I have been waiting two years for my children's answer. It's not now that I'm going to start launching a project, neither in the vineyard, nor in my head.*" (Grower 7). Conversely, sustainable farms may follow two distinct paths that involve grape varieties and landscape reorganisation. One category of growers argues for crop diversification by embracing aromatic plants, hops and barley for beer production and fruit orchards, with an emphasis on direct sales. They also talk about territorial identity via the cultivation of locally distinct grape varieties:

"*Some growers choose to return to a human-sized vineyard based on the know-how of their forefather, keeping only the Gaillac local grape varieties […] Agricultural specialisation is a recipe for disaster, whereas diversification is the future of our business. That's why I'm going to put apple trees instead of Syrah, make my beer, grow and sell aromatic plants like lavender. There is a market for this type of farm, as long as the grower is consistent between his practices and his image.*" (Grower 2).

For some growers, the seniority of local varieties in the area suggests that these varieties are highly suited to the terroir, allowing the growers to obtain the appropriate balance in terms of sugar, acidity and other compounds. Because these grape varieties have been cultivated regionally for several centuries in the wine-growing area, growers argue that they are "*experienced and survived several crisis, such as phylloxera and past climate change*", as noted by grower 22. By contrast, another category of growers pleads for one-third AOC and two-thirds IGP farm area as a rule of thumb:

"We have been on a mixed vineyard in terms of quality and quantity for 100 years, I don't see why we wouldn't be mixed tomorrow. On the other hand, we produce too much AOC compared to what we can sell. There are two solutions, uproot the vines or put them in a functional scheme. The scheme that works is to adapt to a market where 80 % of consumers want generic wines and 20 % of consumers want terroir-based wines." (Grower 4).

This group of growers plans to position AOC production on hillsides using local grape varieties and IGP production in the valleys using international grape varieties by combining irrigation, frost insurance and mechanical pruning for higher productivity. Emphasis will be placed on market diversification by producing both high-quality and generic wine for several outlets, including supermarket, restaurant, exportation and direct sales. However, this template is criticised by others growers, who i) may not have the assets to diversify their farms, and ii) as a result of their ecological values or ethics, refuse the use of irrigation and mechanical pruning.

Having to cope with climate change impacts on grape varieties, social demands and on-going environmental regulations about pesticide reduction is forcing both growers and institutions to further integrate environmental factors into their grape management.

As the local climate shifts, the yield and organoleptic properties of early-season varieties with low heat-tolerance, such as Gamay, could be severely impacted, leading to their decline and sometimes abandonment. Conversely, later-season grape varieties, like Syrah or Muscadelle (which usually rots before harvest), are grown further up the hillside and the white varieties on the northern slopes. In addition, growers are beginning to rely on a new diversity of varieties and rootstocks that can cope with new temperature regimes through well-adapted functional traits, such as a later phenological events or better sugar-acidity balance (e.g., Bouysselet, Jurancon noir or Cinsaut) and drought-resistant rootstocks (R110 and Ru 140 on limestone soils) for new plantings. We expect that this will become more important as growers attach more and more importance to plant traits related to climate. As grower 22 noted: "*I want to plant Chenin […] But when I think about the evolution of the climate, I wonder if it is wise to plant Chenin in Gaillac, because it appreciates cool temperatures and it is sensitive to late-spring frost. […] Ten years ago, I would have done it without thinking about it*". Moreover, growers are actually turning to or considering research-supported disease-resistant (downy and powdery mildews) grape varieties, such as Floreal or Artaban, while other growers are experimenting with old American hybrids like Noah or Othello. However, a majority of growers are still skeptical about these varieties, as they do not have enough knowledge about their susceptibility to trunk diseases, organoleptic potential and marketing opportunities.

Market demands, climate change and the need to reduce the use of synthetic chemicals in vineyards all call for increased flexibility and creativity in the selection of varieties. First, the new CAP reform (2023-2027) will allow growers to use disease-resistant varieties for AOC wine production. In addition, the INAO approved in 2018 the framework of the Variétés d'Intérêt à Fin d'Adaptation (VIFA) to experiment on new varieties; i.e., up to 5 % of the cultivated areas of a farm and up to 10 % of the mixtures over a period of 5 years (renewable once). How this translates into specific prescriptions within appellations, however, can vary depending on the influence of individual and institutional actors, including appellation syndicates, as well as the specifics of the growing conditions. Some appellations have already undertaken this testing device by reintroducing local, foreign or hybrid varieties. For instance, the Bordeaux region is experimenting with the Castets, Touriga Nacional and Alvarinho among the six approved VIFAs; and the Champagne region recently confirmed the application for approval of the hybrid variety that is resistant to downy and powdery mildew, known as Voltis, for the production of Champagne AOC. In the southwestern region and in Gaillac, VIFA measures are still under consideration and research institutes are listening to the needs of management bodies.

CONCLUSIONS

Our results highlight that despite the decrease in farm numbers and area, Gaillac vineyards are still diverse. Due to many grape varieties being available and terroir being heterogeneous, a large number of variations in wine-growing and winemaking systems are possible. Wine-growing is often perceived as a fixed system, but it has never stopped adapting. Different drivers, such as market integration and transformation, policy changes, demographic pressures, institutions and regulations, the development of new technologies and practices, have strongly contributed to grape diversity change over time and space at local scale. Whether seeking a niche market or a standardised market, the dynamics of grape varietal choice have been largely driven by market needs, and the choice is applied according to regulatory frameworks. Many case studies point out that farmers appear very sensitive to economic opportunities (Labeyrie *et al*., 2021). Feintrenie *et al*. (2010), for example, observed in Indonesian agroforestry systems that economic dimension takes precedence over other values, such as cultural or sentimental attachment, and can quickly transform a diversified system into a monoculture. However, our study found that market integration does not necessarily mean lower crop diversity, as documented in previous studies (Goldberg *et al*., 2021; Vadez *et al*., 2004).

Growers organise their grape portfolios to safeguard livelihoods in the future by ensuring new marketing opportunities. Thanks to cultural heritage and a strong attachment-to-place, the Gaillac region has one of the most diverse variety portfolios in France. Since diversification has been shown to be an important factor in mitigating the effects of climate change in vineyards (Morales-Castilla *et al*., 2020) and in agriculture more generally (Altieri *et al*., 2015), the results suggest that Gaillac vineyards may be relatively well-constituted for offsetting climate change impacts.

Driven by growing concerns about environmental constraints, the crop trends we identified suggest a future evolution of grape portfolios. Recent political measures (national catalogue, CAP and VIFA) are allowing the wine-growing sector to increase in diversity at the local scale. This flexibility in the selection of varieties could enhance and strengthen the resilience of wine-growing systems at local scale in a future of dramatic environmental stresses.

To adapt to an ever-changing future, it is pivotal to pave the way for dynamic grape diversity management involving collaborative relationships between growers, researchers, conservatories and institutions that control regulations.

ACKNOWLEDGEMENTS

The research for this article was supported by the French National Research Agency (ANR) as part of the Programme d'Investissements d'Avenir (reference 17- MPGA-0004). We are most grateful for the time that growers from Gaillac generously offered to answer our questions. We would like to thank T. Lacombe and C. Marchal who helped to obtain data from the INRAE Domaine de Vassal Grape Collection, X. Raffenne and C. Granado from La Maison des Vins de Gaillac who helped with historical documents research, and C. Monmarthe from the French customs services who facilitated the handling of the CVI dataset.

REFERENCES

Aigrain, P., Bois, B., Brugière, F., Duchene, E., de Cortázar-Atauri, G., Gautier, J., Hannin, H., Ollat, N., & Touzard, J.-M. (2021). *Quelles actions pour la filière vigne et vin face au changement climatique ? : Sélection de propositions issues d'une démarche participative et de la consultation d'instances professionnelles viticoles*. INRAE. https://doi.org/10.15454/AHD9-E468

Alleweldt, G., & Possingham, J. V. (1988). Progress in grapevine breeding. *Theoretical and Applied Genetics*, *75*(5), 669–673. https://doi.org/10.1007/BF00265585

Alston, J. M., & Sambucci, O. (2019). Grapes in the World Economy. In D. Cantu & M. A. Walker (Eds.), *The Grape Genome* (pp. 1–24). Springer International Publishing. https://doi.org/10.1007/978-3-030-18601-2_1

Altieri, M. A., Nicholls, C. I., Henao, A., & Lana, M. A. (2015). Agroecology and the design of climate change-resilient farming systems. *Agronomy for Sustainable Development*, *35*(3), 869–890. https://doi.org/10.1007/s13593-015-0285-2

Anderson, K., & Nelgen, S. (2020). Which winegrape varieties are grown where? A global empirical picture (revised edition). *Adelaide: University of Adelaide Press*.

Anderson, K., & Nelgen, S. (2021). Internationalization, premiumization and diversity of the world's winegrape varieties. *Journal of Wine Research*, *32*(4), 247–261. https://doi.org/10.1080/09571264.2021.2012444

Anderson, K., & Nelgen, S. (2022). Internationalisation of winegrape varieties and its implications for terroir-based cultural assets. In *The Routledge Handbook of Wine and Culture*. https://doi.org/10.4324/9781003034711-47

Anderson, K., Nelgen, S., & Pinilla, V. (2017). *Global wine markets, 1860 to 2016: A statistical compendium*. University of Adelaide Press. https://doi.org/10.20851/global-wine-markets

Avallone, N., Berramdane, A., Guillard, C., Lammoglia, A., Leturcq, S., & Thillaye, S. (2018). L'Union européenne et les dynamiques spatiales du vignoble français (1962-2016). *Revue du droit de l'Union européenne*, 141–168.

Barber, N., Dodd, T., & Ghiselli, R. (2008). Capturing the Younger Wine Consumer. *Journal of Wine Research*, *19*(2), 123–141. https://doi.org/10.1080/09571260802622225

Bavaresco, L. (2019). Impact of grapevine breeding for disease resistance on the global wine industry. *Acta Horticulturae*, *1248*, 7–14. https://doi.org/10.17660/ActaHortic.2019.1248.2

Béringuier, C. (1986). La viticulture dans le Midi pyrénéen. *Revue géographique des Pyrénées et du Sud-Ouest*, *57*(1), 73–88. https://doi.org/10.3406/rgpso.1986.3041

Berkes, F., Colding, J., & Folke, C. (2000). Rediscovery of traditional ecological knowledge as adaptative management. *Ecological Applications*, *10*(5), 1251–1262. https://doi.org/10.1890/1051-0761(2000)010[1251:ROTEKA]2.0.CO;2

Bertrand, N., & Bertrand, N. (2013). Terres agricoles périurbaines : Une gouvernance foncière en construction. In *Terres agricoles périurbaines : Une gouvernance foncière en construction* (pp. 9–18). Editions Quae. https://hal.inrae.fr/hal-02604616

Blonde, P., Hochereau, F., Barbier, J. M., & Touzard, J.-M. (2016). Vignes résistantes à l'oïdium et au mildiou: Promesses et controverses en Languedoc-Roussillon. *Courrier de l'Environnement de l'INRA*, *66*, 69–82.

Boursiquot, J. M., & This, P. P. (1999). Essai de définition du cépage. *Progrès Agricole et Viticole*, *116*(17), 359–361.

Brun, F. (1974). La réinstallation des agriculteurs pieds-noirs dans le Midi méditerranéen. *Annales de Géographie*, *83*(460), 676–683. https://doi.org/10.3406/geo.1974.18960

Brush, S. B., Carney, H. J., & Humán, Z. (1981). Dynamics of Andean potato agriculture. *Economic Botany*, *35*(1), 70–88. https://doi.org/10.1007/BF02859217

Caillon, S. (2005). Les taros du Vanuatu: Que conserver et comment ? *Natures Sciences Sociétés*, *13*(3), 306–310. https://doi.org/10.1051/nss:2005047

Carew, R., & Florkowski, W. J. (2008). *The Importance of Australian Corporate Brand and Grape Varietal Wines: Hedonic Pricing in the British Columbia Wine Market*. 11. https://doi.org/10.1017/S1931436100001218

Cavaillé, A. (1975). *Le vignoble de Gaillac », Recueil des actes du millénaire de Gaillac 972-1972.*

Chambre d'Agriculture. (2020). *L'agriculture tarnaise en bref. Tableau de bord de l'agriculture.*

De la Fuente Lloreda, M. (2018). Use of hybrids in viticulture. A challenge for the OIV. *OENO One*, *52*(3), 231–234. https://doi.org/10.20870/oeno-one.2018.52.3.2312

Delaunois, A., Jarno, J.-N., & Yobregat, O. (1996). *Description des differents terroirs du Gaillacois*. Chambre d'agriculture du Tarn.

Demossier, M. (2020). *Burgundy: The global story of terroir*. Berghahn.

Dray, S., Bauman, D., Blanchet, G., Borcard, D., Clappe, S., Guenard, G., Jombart, T., Larocque, G., Legendre, P., Madi, N., & Wagner, H. H. (2021). *adespatial: Multivariate Multiscale Spatial Analysis*. https://CRAN.R-project.org/package=adespatial

Elias, M., Rival, L., & McKey, D. (2000). Perception and management of cassava (Manihot esculenta Crantz) diversity among Makushi Amerindians of Guyana (South America). *Journal of Ethnobiology*, *20*(2), 239–265.

FAO (2010). *The second report on the state of the world's plant genetic resources for food and agriculture*. FAO (Eds.).

Feintrenie, L., Schwarze, S., & Levang, P. (2010). Are Local People Conservationists? Analysis of Transition Dynamics from Agroforests to Monoculture Plantations in Indonesia. *Ecology and Society*, *15*(4), art37. https://doi.org/10.5751/ES-03870-150437

FranceAgrimer (2022). *Catalogue national officiel des variétés (plants de vigne)—Liste A : variétés de vigne inscrites dont les matériels de multiplication peuvent être commercialisés au sein de l'Union européenne*. 12.

Gade, D. W. (2004). Tradition, Territory, and Terroir in French Viniculture: Cassis, France, and Appellation Contrôlée. *Annals of the Association of American Geographers*, *94*(4), 848–867.

Gale, G. (2011). *Dying on the Vine: How Phylloxera Transformed Wine.* (University of California Press). https://doi.org/10.1525/9780520948853

Galet, P. (1988). *Cépages et vignobles de France* (2e éd., entièrement ref). C. Déhan.

Garcia-Parpet, M.-F. (2008). Markets, prices and symbolic value: *Grands crus* and the challenges of global markets. *International Review of Sociology*, *18*(2), 237–252. https://doi.org/10.1080/03906700802087910

Goldberg, Z. A., Powell, B., & Ouarghidi, A. (2021). Determinants of Smallholder Maintenance of Crop Diversity in Morocco's High Atlas Mountains. *Human Ecology*, *49*(4), 453–465. https://doi.org/10.1007/s10745-021-00248-7

Grassi, F., & De Lorenzis, G. (2021). Back to the Origins: Background and Perspectives of Grapevine Domestication. *International Journal of Molecular Sciences*, *22*(9), 4518. https://doi.org/10.3390/ijms22094518

Gray, J. (2000). The Common Agricultural Policy and the Re-Invention of the Rural in the European Community. *Sociologia Ruralis*, *40*(1), 30–52. https://doi.org/10.1111/1467-9523.00130

Heckler, S., & Zent, S. (2008). Piaroa Manioc Varietals: Hyperdiversity or Social Currency? *Human Ecology*, *36*(5), 679–697. https://doi.org/10.1007/s10745-008-9193-2

Humbert, F. (2011). *L'INAO, de ses origines à la fin des années 1960: Genèse et évolutions du système des vins d'AOC*. 756.

INAO (2020). *Les produits sous signe d'identification de la qualité et de l'origine. Chiffres-clés 2020.* https://www.inao.gouv.fr/content/download/4011/35006/version/2/file/INAO%20-%2012P%20chiffres-cle%CC%81s%202021%20BD.pdf

IVSO (2017). *Evolution du vignoble Tarnais.* Interprofession des Vins du Sud-Ouest.

Jarvis, D. I., Brown, A. H. D., Cuong, P. H., Collado-Panduro, L., Latournerie-Moreno, L., Gyawali, S., Tanto, T., Sawadogo, M., Mar, I., Sadiki, M., Hue, N. T.-N., Arias-Reyes, L., Balma, D., Bajracharya, J., Castillo, F., Rijal, D., Belqadi, L., Rana, R., Saidi, S., … Hodgkin, T. (2008). A global perspective of the richness and evenness of traditional crop-variety diversity maintained by farming communities. *Proceedings of the National Academy of Sciences*, *105*(14), 5326–5331. https://doi.org/10.1073/pnas.0800607105

Kenny, G. J., & Harrison, P. A. (1992). The effects of climate variability and change on grape suitability in Europe. *Journal of Wine Research*, *3*(3), 163–183. https://doi.org/10.1080/09571269208717931

Khoury, C. K., Brush, S., Costich, D. E., Curry, H. A., Haan, S., Engels, J. M. M., Guarino, L., Hoban, S., Mercer, K. L., Miller, A. J., Nabhan, G. P., Perales, H. R., Richards, C., Riggins, C., & Thormann, I. (2022). Crop genetic erosion: Understanding and responding to loss of crop diversity. *New Phytologist*, *233*(1), 84–118. https://doi.org/10.1111/nph.17733

Kremen, C., & Miles, A. (2012). Ecosystem Services in Biologically Diversified versus Conventional Farming Systems: Benefits, Externalities, and Trade-Offs. *Ecology and Society*, *17*(4), art40. https://doi.org/10.5751/ES-05035-170440

Labeyrie, V., Renard, D., Aumeeruddy-Thomas, Y., Benyei, P., Caillon, S., Calvet-Mir, L., M. Carrière, S., Demongeot, M., Descamps, E., Braga Junqueira, A., Li, X., Locqueville, J., Mattalia, G., Miñarro, S., Morel, A., Porcuna-Ferrer, A., Schlingmann, A., Vieira da Cunha Avila, J., & Reyes-García, V. (2021). The role of crop diversity in climate change adaptation: Insights from local observations to inform decision making in agriculture. *Current Opinion in Environmental Sustainability*, *51*, 15–23. https://doi.org/10.1016/j.cosust.2021.01.006

Lavignac, G. (2001). *Cépages du sud-ouest: 2000 ans d'histoire ; mémoires d'un ampélographe*. Ed. du Rouergue [u.a.].

Legendre, P. (2019). A temporal beta-diversity index to identify sites that have changed in exceptional ways in space–time surveys. *Ecology and Evolution*, *9*(6), 3500–3514. https://doi.org/10.1002/ece3.4984

Legendre, P., & De Cáceres, M. (2013). Beta diversity as the variance of community data: Dissimilarity coefficients and partitioning. *Ecology Letters*, *16*(8), 951–963. https://doi.org/10.1111/ele.12141

Lima, T. (2006). Price and Quality in the California Wine Industry: An Empirical Investigation. *Journal of Wine Economics*, *1*(2), 176–190. https://doi.org/10.1017/S1931436100000201

Lin, B. B. (2011). Resilience in Agriculture through Crop Diversification: Adaptive Management for Environmental Change. *BioScience*, *61*(3), 183–193. https://doi.org/10.1525/bio.2011.61.3.4

Loreau, M., & de Mazancourt, C. (2008). Species Synchrony and Its Drivers: Neutral and Nonneutral Community Dynamics in Fluctuating Environments. *The American Naturalist*, *172*(2), E48–E66. https://doi.org/10.1086/589746

Maraš, V., Tello, J., Gazivoda, A., Mugoša, M., Perišić, M., Raičević, J., Štajner, N., Ocete, R., Božović, V., Popović, T., García-Escudero, E., Grbić, M., Martínez-Zapater, J. M., & Ibáñez, J. (2020). Population genetic analysis in old Montenegrin vineyards reveals ancient ways currently active to generate diversity in *Vitis vinifera*. *Scientific Reports*, *10*(1), 15000. https://doi.org/10.1038/s41598-020-71918-7

Martin, A. R., Cadotte, M. W., Isaac, M. E., Milla, R., Vile, D., & Violle, C. (2019). Regional and global shifts in crop diversity through the Anthropocene. *PLOS ONE*, *14*(2), e0209788. https://doi.org/10.1371/journal.pone.0209788

McDaniel, M. D., Tiemann, L. K., & Grandy, A. S. (2014). Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. *Ecological Applications*, *24*(3), 560–570. https://doi.org/10.1890/13-0616.1

Meloni, G., Anderson, K., Deconinck, K., & Swinnen, J. (2019). Wine Regulations. *Applied Economic Perspectives and Policy*, *41*(4), 620–649. https://doi.org/10.1093/aepp/ppz025

Montaigne, E., & Coelho, A. M. (2006). *La réforme de l'Organisation commune du marché vin*. 91.

Morales-Castilla, I., García de Cortázar-Atauri, I., Cook, B. I., Lacombe, T., Parker, A., van Leeuwen, C., Nicholas, K. A., & Wolkovich, E. M. (2020). Diversity buffers winegrowing regions from climate change losses. *Proceedings of the National Academy of Sciences*, 201906731. https://doi.org/10.1073/pnas.1906731117

Moran, W. (1993). The Wine Appellation as Territory in France and California. *Annals of the Association of American Geographers*, *83*(4), 694–717. https://doi.org/10.1111/j.1467-8306.1993.tb01961.x

Morton, V., & Staub, T. (2008). A Short History of Fungicides. *APSnet Feature Articles*. https://doi.org/10.1094/APSnetFeature-2008-0308

Myles, S., Boyko, A. R., Owens, C. L., Brown, P. J., Grassi, F., Aradhya, M. K., Prins, B., Reynolds, A., Chia, J.-M., Ware, D., Bustamante, C. D., & Buckler, E. S. (2011). Genetic structure and domestication history of the grape. *Proceedings of the National Academy of Sciences*, *108*(9), 3530–3535. https://doi.org/10.1073/pnas.1009363108

Nicholas, K. A., & Durham, W. H. (2012). Farm-scale adaptation and vulnerability to environmental stresses: Insights from winegrowing in Northern California. *Global Environmental Change*, *22*(2), 483–494. https://doi.org/10.1016/j.gloenvcha.2012.01.001

Oksanen, J., Blanchet, F. G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P. R., O'Hara, R. B., Simpson, G. L., Solymos, P., Stevens, M. H. H., Szoecs, E., & Wagner, H. (2019). *vegan: Community Ecology Package*. https://CRAN.R-project.org/package=vegan

Olivier de Sardan, J.-P. (1995). La politique du terrain: Sur la production des données en anthropologie. *Enquête*, *1*, 71–109. https://doi.org/10.4000/enquete.263

Pawlak, K., Smutka, L., & Kotyza, P. (2021). Agricultural Potential of the EU Countries: How Far Are They from the USA? *Agriculture*, *11*(4), 282. https://doi.org/10.3390/agriculture11040282

Plageoles, R. (2006). *La saga des cépages gaillacois et tarnais en 2.000 ans d'histoire*. J.-P. Rocher.

QGIS.org (2022). *QGIS Geographic Information System* (3.10) [Computer software]. QGIS Association. http://www.qgis.org

R Core Team (2021). *R: A language and environment for statistical computing*. (3.6.2) [Computer software]. R Foundation for Statistical Computing. https://www.R-project.org/

Registre Parcellaire Graphique (2017). Registre Parcellaire Graphique (RPG), éditions de 2017 : contours des parcelles et îlots culturaux et leur groupe de cultures majoritaire. *Institut National de l'Information Géographique et Forestière (IGN)*. https://www.data.gouv.fr/fr/datasets/registre-parcellaire-graphique-rpg-contours-des-parcelles-et-ilots-culturaux-et-leur-groupe-de-cultures-majoritaire/

Renard, D., & Tilman, D. (2019). National food production stabilized by crop diversity. *Nature*, *571*(7764), 257–260. https://doi.org/10.1038/s41586-019-1316-y

Reynier, A. (2012). *Manuel de viticulture: Guide technique du viticulteur*. Tec & Doc.

Riol, J.-L. (1913). *Le vignoble de Gaillac depuis ses origines jusqu'à nos jours et l'emploi des vins de Bordeaux.*

Robinson, J., & Harding, J. (2015). *The Oxford Companion to Wine* (4th ed.). Oxford University Press. https://doi.org/10.1093/acref/9780198705383.001.0001

Rouvellac, É. (2008). Les spécificités et les difficultés du vignoble gaillacois, un siècle de reconstruction et de reconnaissance de la qualité. *La vigne en Méditerranée occidentale*, 89–102.

Santos, J. A., Fraga, H., Malheiro, A. C., Moutinho-Pereira, J., Dinis, L.-T., Correia, C., Moriondo, M., Leolini, L., Dibari, C., Costafreda-Aumedes, S., Kartschall, T., Menz, C., Molitor, D., Junk, J., Beyer, M., & Schultz, H. R. (2020). A Review of the Potential Climate Change Impacts and Adaptation Options for European Viticulture. *Applied Sciences*, *10*(9), 3092. https://doi.org/10.3390/app10093092

Schneider, C., Onimus, C., Prado, E., Dumas, V., Wiedemann-Merdinoglu, S., Dorne, M. A., Lacombe, M. C., Piron, M. C., Umar-Faruk, A., Duchêne, E., Mestre, P., & Merdinoglu, D. (2019). INRA-ResDur: The French grapevine breeding programme for durable resistance to downy and powdery mildew. *Acta Horticulturae*, *1248*, 207–214. https://doi.org/10.17660/ActaHortic.2019.1248.30

Schultz, H. R. (2003). Differences in hydraulic architecture account for near-isohydric and anisohydric behaviour of two field-grown *Vitis vinifera* L. cultivars during drought: Hydraulic conductance and stomatal behaviour. *Plant, Cell & Environment*, *26*(8), 1393–1405. https://doi.org/10.1046/j.1365-3040.2003.01064.x

Snapp, S. S., Blackie, M. J., Gilbert, R. A., Bezner-Kerr, R., & Kanyama-Phiri, G. Y. (2010). Biodiversity can support a greener revolution in Africa. *Proceedings of the National Academy of Sciences*, *107*(48), 20840–20845. https://doi.org/10.1073/pnas.1007199107

Spach, M. (2016). Enjeux économiques et politiques publiques de lutte contre la consommation nocive d'alcool en France: *Santé Publique*, *Vol. 28*(4), 461–470. https://doi.org/10.3917/spub.164.0461

Tallavignes, Ch. (1902). Duras. In *Traité général de viticulture – Ampélographie.* (Viala P., Vermorel V., Vol. 3). Masson. https://gallica.bnf.fr/ark:/12148/bpt6k6532246j

This, P., Lacombe, T., & Thomas, M. (2006). Historical origins and genetic diversity of wine grapes. *Trends in Genetics*, *22*(9), 511–519. https://doi.org/10.1016/j.tig.2006.07.008

Tilman, D., Wedin, D., & Knops, J. (1996). Productivity and sustainability influenced by biodiversity in grassland ecosystems. *Nature*, *379*(6567), 718–720. https://doi.org/10.1038/379718a0

Toujas-Pinède, C. (1965). Les rapatriés d'Algérie dans la région Midi-Pyrénées. *Revue géographique des Pyrénées et du Sud-Ouest*, *36*(4), 321–372. https://doi.org/10.3406/rgpso.1965.2175

Touzard, J.-M., & Laporte, J.-P. (1998). Deux décennies de transition viticole en Languedoc-Roussillon : De la production de masse à une viticulture plurielle. *Pôle Sud*, *9*(1), 26–47. https://doi.org/10.3406/pole.1998.1010

Vadez, V., Reyes-García, V., Godoy, R. A., Apaza, V. L., Byron, E., Huanca, T., Leonard, W. R., Pérez, E., & Wilkie, D. (2004). Brief Communication: Does Integration to the Market Threaten Agricultural Diversity? Panel and Cross-Sectional Data From a Horticultural-Foraging Society in the Bolivian Amazon. *Human Ecology, 32*(5), 635–646. https://doi.org/10.1007/s10745-004-6100-3

Van Leeuwen, C., & Seguin, G. (2006). The concept of terroir in viticulture. *Journal of Wine Research*, *17*(1), 1–10. https://doi.org/10.1080/09571260600633135

Verdonk, N. R., Wilkinson, K. L., & Bruwer, J. (2015). Importance, use and awareness of South Australian geographical indications: Geographical indications: importance and use. *Australian Journal of Grape and Wine Research, 21*(3), 361–366. https://doi.org/10.1111/ajgw.12145

Wolkovich, E. M., Burge, D. O., Walker, M. A., & Nicholas, K. A. (2017). Phenological diversity provides opportunities for climate change adaptation in winegrapes. *Journal of Ecology*, *105*(4), 905–912. https://doi.org/10.1111/1365-2745.12786

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*, *8*(1), 29–37. https://doi.org/10.1038/s41558-017-0016-6

Yachi, S., & Loreau, M. (1999). Biodiversity and ecosystem productivity in a fluctuating environment: The insurance hypothesis. *Proceedings of the National Academy of Sciences*, *96*(4), 1463–1468. https://doi.org/10.1073/pnas.96.4.1463