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SPECIAL ISSUE

Dating of old vineyards: A multidisciplinary, non-invasive approach for age validation developed in Campo de Borja (Spain)

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ABSTRACT

The P.D.O. Campo de Borja faces a challenge regarding its viticultural heritage, where the total Grenache surface area, over 2000 ha, is estimated to be between 30 and 50 years old, while 144 ha exceed 50 years old. Dating these vineyards could be important for their preservation and commercial valorisation. However, official records occasionally lack sufficiently detailed information about the planting dates. For this reason, this study aims to provide a tool for the certification and management of 'old vineyards' by combining historical aerial photographs, morphological characterisation, and plant material analysis. The aerial photography methodology integrated a time series of aerial photographs, from the American flight (1956–1957) to current PNOA flights (2024), providing insights into possible planting years as well as the spatial patterns and training systems of the plots. The results show that traditional free goblet bushvine systems consistently exceeded mean ages of 45–50 years, with the *tresbolillo* pattern reaching the highest age ranges. In contrast, modern trellised systems and wider inter-row spacing (3–3.5 m) were 17 years old on average. Furthermore, morphological analysis was useful for refining age ranges obtained through aerial photography. Finally, the identification of plant material allowed for the classification of vineyards into three age groups based on the specific rootstocks identified. Overall, this study shows that combining multidisciplinary methodologies can refine the estimation of planting years, providing a basis for the official certification of historical plots and the long-term management of the viticultural landscape.

KEYWORDS: Terclim 2026, geospatial analysis, morphological study, varietal identification, Grenache, viticultural heritage

INTRODUCTION

The concept of 'old vineyard' has gained increasing relevance in contemporary viticulture due to its association with wine quality. Authors such as Grigg *et al.* (2018) highlight that it is difficult to separate the effect of age from other factors such as climate or soil. However, an objective fact is that as vines age, physiological changes typically lead to a decrease in average yields, which results in more concentrated grapes and, consequently, wines with greater intensity (Sanmartin *et al.*, 2017). Furthermore, these vineyards possess a specific character and singular expressions of *terroir*. This typicity, as defined by Souza Gonzaga *et al.* (2021), represents a combination of unique characteristics, involving both biophysical and human dimensions, that make the wines recognisable and impossible to replicate in another territory. To protect and recognise this intrinsic value, the International Organization of Vine and Wine recently established a formal technical criterion, defining an 'old vineyard' as one where at least 85 % of the vines are 35 years or older (OIV, 2024). The certification of this longevity is essential not only for heritage preservation but also for its commercial impact. As highlighted by the OIV (2024), there is a growing need to understand consumer perception of 'old vineyard' labelling, as these indications are often associated with prestige and authenticity. In this regard, consumers frequently use origin as a way to judge quality, demonstrating a higher willingness to pay for wines that guarantee such typicity (Souza Gonzaga *et al.*, 2022). Therefore, the sensory profile of a wine produced from grapes of an 'old vineyard' is not just a biological characteristic but a key factor in the market that demands objective validation. Furthermore, some regions have developed even more specific classifications. For instance, the Barossa Old Vine Charter (Barossa Grape & Wine Association, 2017) distinguishes between Old (≥ 35 years), Survivor (≥ 70), Centenarian (≥ 100), and Ancestor (≥ 125) vineyards (Wine Australia, 2022). However, the scarcity of historical planting records and, as the OIV emphasises, the lack of standardised protocols to identify 'old vineyards' limits the objective classification of vineyard age in many regions, underscoring the necessity of adopting methodologies from other fields, such as forest sciences. One such technique, dendrochronology, which analyses the radial growth rings of the vine trunk, has proven effective in some contexts for dating *Vitis vinifera* plants (Camarero *et al.*, 2024). However, the requirement of obtaining transversal sections of the basal trunk for reliable analysis makes this technique destructive or highly invasive. This restriction invalidates its application for large-scale certification in productive vineyards, creating a need for non-invasive and probabilistic methods that integrate multiple indicators to estimate vine age.

In this scenario, the P.D.O. Campo de Borja faces a particular challenge: out of a total surface area of approximately 4,000 ha of Grenache, over 2,000 ha are estimated to be between 30 and 50 years old, while 144 ha are estimated to be older than 50 years (Denominación de Origen Campo de Borja. El Imperio de La Garnacha, 2025). This heritage requires both commercial valorisation of the wines produced and preservation. Consequently, the 'Garnachas Históricas' project was created to develop a scientific and multidisciplinary method for classifying vineyards based on verifiable indirect indicators. The central hypothesis is that a plot's spatial pattern, vine training systems, and their morphological characteristics constitute indicators of its age.

Regarding spatial pattern and training systems, Spanish viticulture before the 1970s was characterised by traditional management where the '*marco real*' (square pattern) and, to a lesser extent, '*tresbolillo*' (triangular pattern) were the predominant layouts, vineyards being trained as free-standing vines and short spur pruning, the traditional free 'goblet bushvine' system. This configuration was replaced by rectangular spacings and trellised training systems accompanying the introduction of more advanced agricultural machinery (García-Escudero & Martínez Zapater, 2022). This geometric evidence can be complemented by the analysis of historical aerial photography to reconstruct the recent history of each plot.

Plant material genetic identity can also provide evidence of vine age. For instance, scion varietal heterogeneity within the vineyard often serves as a marker of their longevity as observed in the neighbouring Navarra region (Urrestarazu *et al.*, 2015). In the case of rootstocks, the use of certain hybrids can also work as a chronological marker. In Spain, after the phylloxera crisis, the reconstruction of vineyards initially relied on vinifera-American hybrids, such as 1202 Couderc or the AxR1 and AxR9 varieties ('A' for Aramon and 'R' for Rupestris), which covered up to 80 % of the surface before their eventual decline due to insufficient resistance. This led to a following transition toward more resistant rootstocks like Rupestris du Lot and, between 1935 and 1950, hybrids derived from *Vitis berlandieri* such as Richter 110, Millerdat et Grasset 41B, or 161-49C (García-Escudero & Martínez Zapater, 2022). Understanding these historical preferences in plant material selection could therefore offer a basis for an approximate prediction of the planting year through on-site ampelographic observations and microsatellite analysis.

The aim of this work is to combine the information sources described above to develop a tool that could be used to probabilistically estimate vineyard age as a potential tool for the official certification of old vineyards.

MATERIALS AND METHODS

1. Study area and plot selection

The study was conducted between 2023 and 2025 in the P.D.O. Campo de Borja, situated in the northwest of the province of Zaragoza (Aragón, Spain), in a transition zone between the Iberian System mountains (Moncayo) and the Ebro Valley. The geoclimatic environment of Campo de Borja is characterised by a marked continental climate with Atlantic winter and Mediterranean summer influence (Ministerio de Agricultura Pesca y Alimentación, 2024). This results in thermal contrasts and low rainfall, with a mean annual temperature of 15.3 °C and a mean annual rainfall ranging

between 350 and 450 mm. The cold and dry north-westerly wind is a predominant climatic factor. Vineyards extend between 350 and 900 meters in altitude, predominantly on brown-calcareous soils and terrace soils with high gravel content and good drainage (Ministerio de Agricultura Pesca y Alimentación, 2024). A total of 80 plots were selected across different municipalities of the P.D.O. Campo de Borja. The detailed characteristics of each studied plot are provided in the Table S1. The selection was performed in collaboration with participating wineries to ensure a representative sample of the area's viticultural heritage. All plots belong to the Grenache variety and include plots with well-documented planting ages and others of unknown age. A multimodal data collection approach was implemented in all selected plots.

2. Compilation and analysis of plot planting history, vine training systems, and spatial pattern, using historical aerial photographs

Historical aerial photographs constitute a valuable documentary resource for researching geographical evolution, as they faithfully reflect the state of a territory at different moments in time. The Instituto Geográfico Nacional indicates that this resource is fundamental for analysing changes in agricultural land use; consequently, aerial images were obtained from this source to reconstruct the history of the study plots. The time series covered a range from the American flight B series (1956–1957) to the current flights of the National Aerial Orthophotography Plan (PNOA) of 2024, provided by the Instituto Geográfico Nacional (Instituto Geográfico Nacional, 2025). The specific flights used as a basis for this study are detailed in Table 1. As can be seen, the availability of graphic information tends to decrease as the analysis goes further back towards the mid-20th century. The historical record starts with the American flight B series and the Interministerial flight, between which there is a time gap of approximately 20 years. Subsequently, the overlap detected between the Interministerial and National flights suggests a greater availability of images during that specific decade. In these cases, the IGN categorises images from various years by general flight names, such as National or Interministerial, with internal time ranges that can vary between 5 and 13 years. To help determine age ranges with greater precision, we have chosen to identify the exact year of acquisition indicated by the IGN within those periods. Regarding more recent stages, the study has relied on the annual PNOA, which offers photography every 2 to 3 years, covering an annual record from 2004 to the present. Finally, the most current PNOA has been used, which provides a mosaic composed of the most recent aerial photographs processed by the IGN. This resource aims to provide the visual representation closest to the current reality of the vineyard for the end of the study in 2025. It is worth noting that the number of available images varies significantly between different locations in Spain. Therefore, this work only details those that specifically cover the study areas.

For image processing and analysis, Geographic Information Systems (QGIS, 3.10.14) software was used. In this software, the historical images were compared with current cartography (PNOA) to ensure correct spatial alignment and minimise the distortions inherent to old aerial photographs. Systematic temporal mosaics were generated for each plot, facilitating temporal review and change identification. This diachronic analysis was used to identify the first visible appearance of the vineyard plantation, establishing a minimum real age for the plot (Figure 1).

TABLE 1. Summary of aerial photographs from the Instituto Geográfico Nacional (IGN) corresponding to the study area.

Flight	Years of flight	Coloring	Pixel size (m)	Month/year or year of the aerial photographs of the study area
American B series	1956–1957	B/W*	0.50–1	1956–1957
Interministerial	1973–1986	B/W	0.25–0.50	08/1977
National	1980–1986	B/W	0.50–1	09/1985
OLISTAT	1997–1998	B/W	1	10/1997
Identification system for agricultural plots (SIGPAC)	1997–2003	Colour	0.50	07/1999
Annual national aerial orthophotography plan (PNOA)	2006	Colour	0.50	2006
	2009	Colour	0.50	2009
	2012	Colour	0.50	2012
	2015	Colour	0.50	2015
	2018	Colour	0.25	2018
	2021	Colour	0.25	2021
Most recent PNOA*	2024	Colour	0.25	07/2024

* Mosaics of the most recent definitive photographs.

*B/W: black and white

The most recent aerial photographs were also used to identify the spatial situation of the vines, which allowed, on the one side to determine if they were trained as goblet (vines seen as individual points) or trellised (seen as rows) and, in the case of goblet vines, to determine their spacing and their planting pattern as *marco real* (square pattern) or *tresbolillo* (triangular pattern) (Figure 2). The potential of aerial imagery for determining the training system was assessed on all the plots we visited (14), and the planting patterns were checked on two plots using a tape measure.

3. Morphological study of the vines

To refine the age of old vines that aerial images cannot detect, a morphological study of the vine trunk was conducted in a subsample of 14 plots (selected from the 80 total plots). This selection was restricted to vineyards classified as old according to P.D.O. records, with their existence verified through visual analysis of the historical photographs series available for the area, thereby ensuring the vines reached a verifiable minimum age. This analysis focused on correlating the physical dimensions of the vine with its potential age. In each of the 14 plots, a targeted sampling was made, and between 6 and 8 vines representative of the overall vineyard average were selected, vines that could be clearly identified to be as old as the vineyard and where the arms appeared to be undamaged or reconstructed to measure. The following morphological variables were recorded in situ during winter, after pruning (Figure 3):

Total length of the vine (L_t): measured in centimetres (cm) from soil level to the last pruning cut in clearly defined arms in each vine.

Number of visible pruning cuts (N_{cuts}): count of visible old wood cuts on the vine, assuming one cut per year.

Total distance between pruning cuts (D_{cuts}): accumulated longitudinal distance between the visible pruning cuts counted, measured in centimetres (cm).

The calculation of the individual vine age (A_{vine}) was performed in two steps. First, the mean annual growth rate (G_{vine}) was determined using the total distance between visible cuts (D_{cuts}) and the number of recorded cuts (N_{cuts}):

$$G_{vine} = \frac{D_{cuts}}{N_{cuts}} \qquad \text{(Equation 1)}$$

where G_{vine} is expressed in cm/year. To establish a chronological reference, a standardised regional growth rate (G_{vine_ref}) was calculated by averaging the individual rates obtained across the 14 sampled vineyards.

Subsequently, the estimated age of the vine (A_{vine}) was calculated by dividing the total vine length (L_t) by this annual growth rate (G_{vine}):

$$A_{vine} = \frac{L_t}{G_{vine}} \qquad \text{(Equation 2)}$$

where A_{vine} is expressed in years.

4. Varietal and rootstock identification

The genetic identity determination of both wine grape cultivars and rootstocks was initiated with field studies conducted across 20 vineyards (14 old, 6 young). During these visits, a detailed ampelographic characterisation was conducted to assess the diversity of the existing plant material. Leaf tissue samples were collected from vines presenting morphological characteristics distinct from the primary cultivar Grenache. Regarding rootstocks, sampling prioritised leaf tissue. However, in vines where canopy sampling was impossible due to mechanical removal of the rootstock vegetation, root samples were collected. Following collection, all samples were placed in coded cryotubes and transported to the laboratory at the Public University of Navarre (UPNA), where they were stored at –80 °C until molecular analysis.

The plant material, cryopreserved leaf tissue and root samples were processed using distinct preparation protocols. Leaf samples were homogenised via mechanical fragmentation with tungsten beads in a microdismembrator (1 minute at 2000 rpm) (B. Braun Biotech International, Melsungen, Germany). In the case of root samples, the bark was removed with a scalpel due to its high polyphenolic content, which can interfere with the extraction process, and then the remaining material was ground with sandpaper to obtain a fine powder.

Genomic DNA isolation was performed using the DNeasy Plant Pro commercial kit (Qiagen), following the manufacturer's instructions. The DNA quality and concentration were determined in a FLUOstar Omega (BMG Labtech). The purified DNA was stored at –20 °C for subsequent analysis. For genetic characterisation, microsatellite loci, or Simple Sequence Repeats (SSRs), were amplified. These regions consist of tandem repeat units where the number of repeats is highly polymorphic among grapevine cultivars, enabling precise identification of varieties. Amplification of the SSR regions was performed using three independent multiplex PCRs denoted as A, B, and C. The reactions were carried out using fluorescently labelled primers and the Multiplex PCR Master Mix (Qiagen®), following the manufacturer's instructions. One primer of each pair was fluorescently labelled with VIC, NED, PET or 6-FAM dyes. Amplification conditions were carried out following the protocols described by Ibáñez *et al.* (2009), with several modifications for A and B multiplex PCRs as detailed in Urrestarazu *et al.* (2015). Fragment analysis was performed in an ABI PRISM 3730 sequencer (Applied Biosystems, Foster City, CA, USA), using 500-LIZ as internal marker size, and the resulting electropherograms were processed to assign fragment sizes with Peak Scanner Software version 1.0 (Applied Biosystems, Foster City, CA, USA). The Table S2 details the SSR marker profile (VVS2, VVMD5, VVMD7, VVMD25, VVMD27, VVMD28, VVMD32, ZAG62 and VRZAG79) used for varietal identification by comparison with reference profiles from the database Vitis International Variety Catalogue (VIVC) (Maul & Töpfer, 2015).

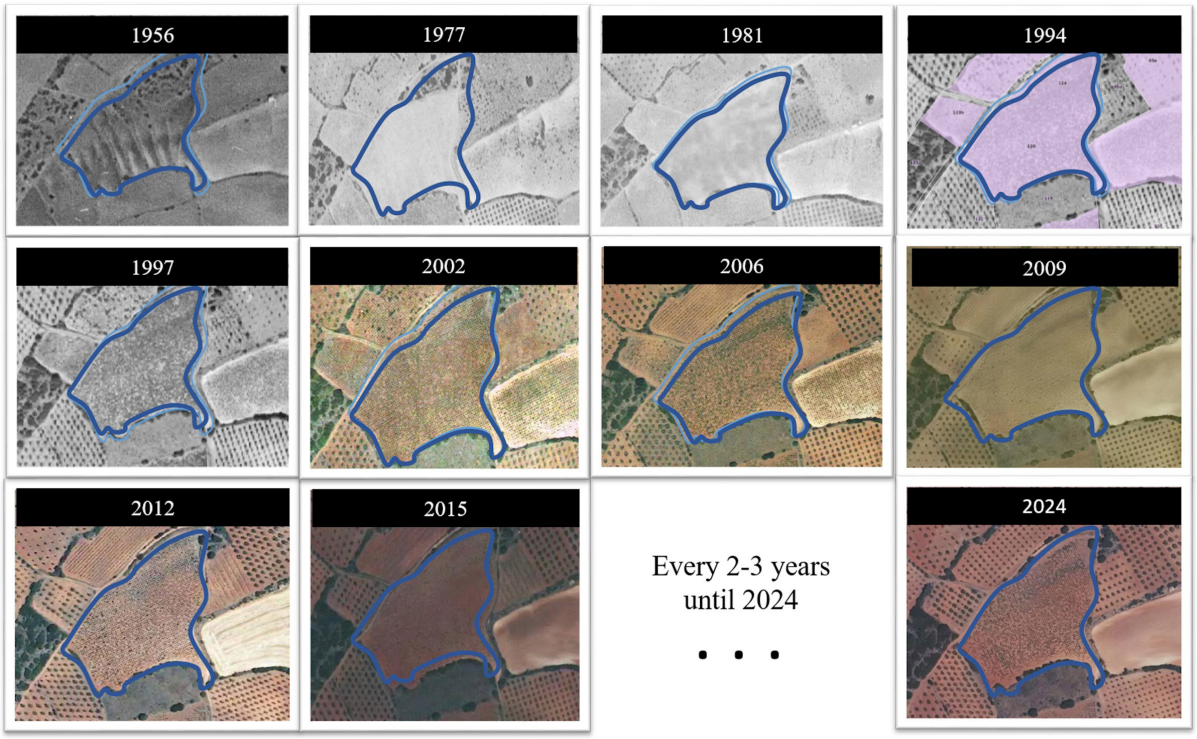


FIGURE 1. Summary of Instituto Geográfico Nacional (IGN) aerial flight photographs used in the study.

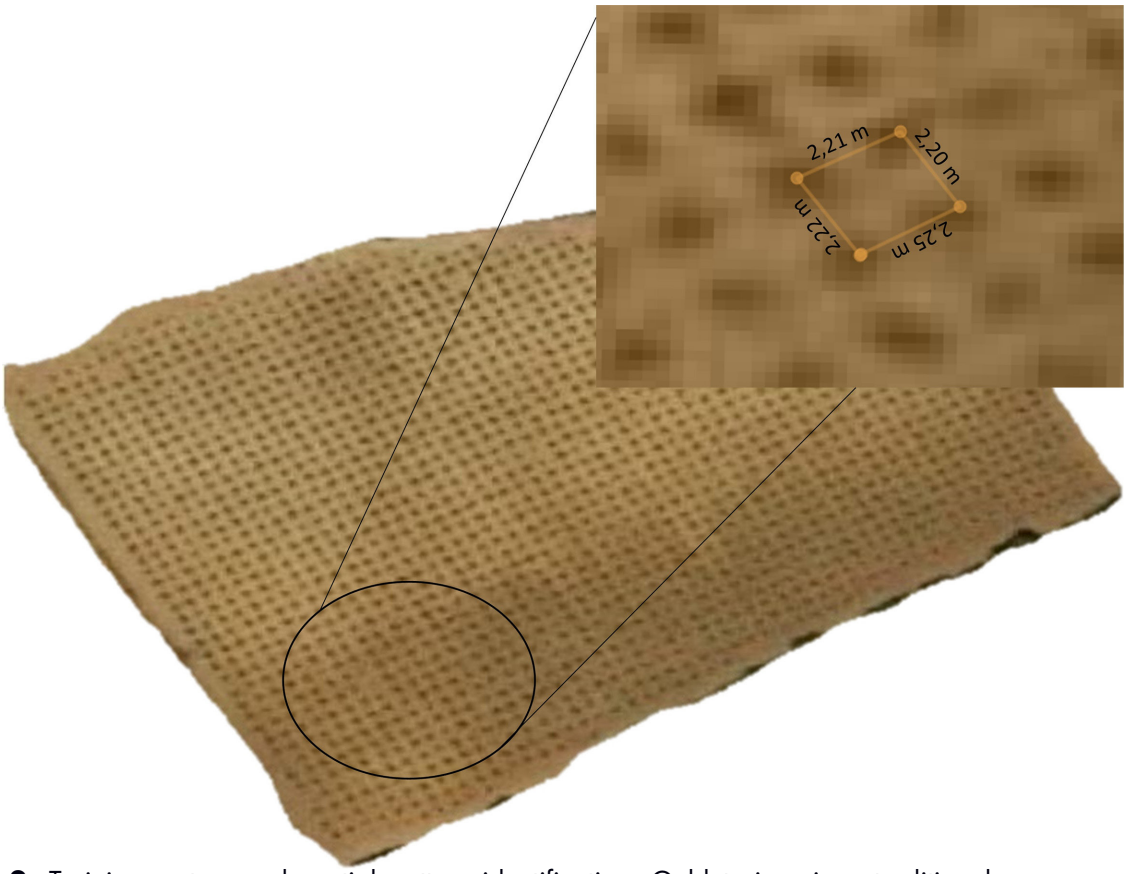


FIGURE 2. Training system and spatial pattern identification: Goblet vines in a traditional marco real pattern, visualised using Geographic Information System software (QGIS v. 3.10.14) on the most recent PNOA aerial photographs (2025).

RESULTS

1. Results from historical aerial photographs study.

The analysis of the 80 selected plots is presented in Table 2, which shows the data obtained from the analysis of historical aerial photography and the vine ages provided by the official D.O.P. Campo de Borja records. Regarding the training systems, which serve as an indicator of planting age, the majority of the surveyed plots (75 %) are planted using a trellis system, while the remaining 25 % consist of goblet vines. Within these goblet-trained vineyards, 70 % follow a *marco real* pattern, whereas the remaining 30 % are established in a *tresbolillo* configuration. Furthermore, an analysis of row spacing shows that 28.8 % of vineyards have a row spacing of 2 to 2.5 m, while the remaining 71.2 % range from 3 to 3.5 m.

To estimate plantation age ranges, we established a chronological timeline using only the available aerial flights with spatial resolution: Interministerial (1977), National flight (1985), OLISTAT (1997), SIGPAC (1999), and PNOA (2006, 2009, 2012, 2015, 2018, 2021, and 2024). The level of uncertainty in the age estimation is defined by the time interval between the first photograph showing the vines and the immediately preceding flight. These ranges are detailed in the final column of Table 2. The maximum uncertainty interval applies to vineyards first identified in 1977, which are estimated to be over 48 years old. Conversely, the minimum intervals range from 1 to 4 years for more recent plantations, due to the increased frequency of aerial surveys. However, it is important to note that local factors such as cloud cover or complex terrain relief occasionally reduced image quality, leading to wider uncertainty intervals in certain locations. When comparing these estimates with the official registered ages (from 3 to 82 years), different degrees of deviation were observed. In some plots (*e.g.*, ID 31 and 35), the registered year matches the age range estimated from aerial photographs. In many other plots, small deviations between 1 and 5 years are present. This range could be considered negligible, as they are a consequence of the gaps between aerial flights. However, larger deviations of up to 35 years exist in specific cases (*e.g.*, ID 7 and 27). These wide intervals are primarily due to the lack of available aerial surveys prior to 1977, an issue that increases the uncertainty of maximums for older vineyards.

The relationship between the official registered age and the data collected from the aerial photography analysis is illustrated in Figure 4. When comparing training systems, a difference in longevity is observed; the mean age of the vineyards planted in goblet is higher than that of plots established with a trellis system. Regarding the spatial pattern, the results indicate that vineyards with a *tresbolillo* configuration have a higher average longevity than those

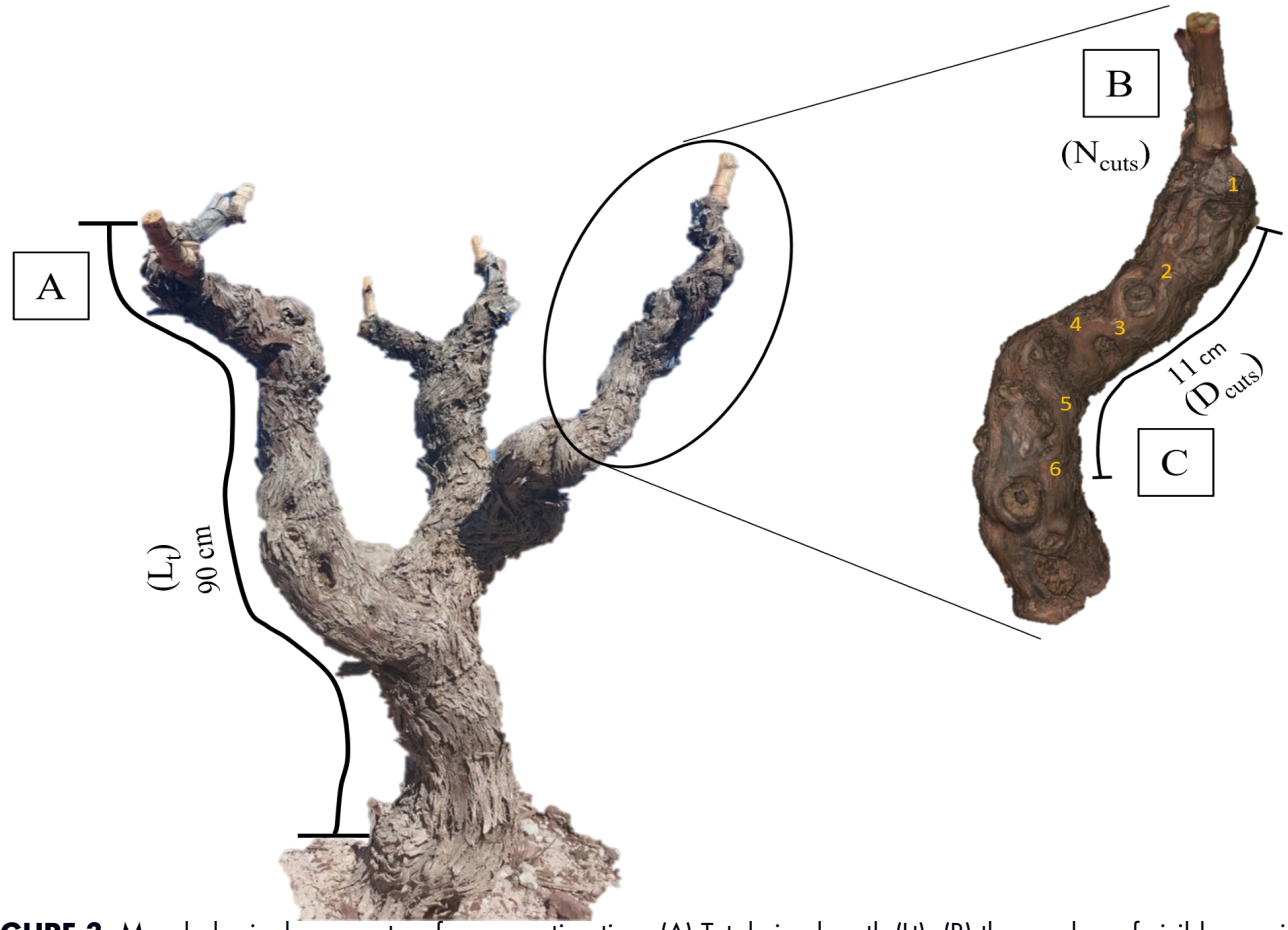


FIGURE 3. Morphological parameters for age estimation: (A) Total vine length (Lt), (B) the number of visible pruning cuts (Ncuts) and (C) the total distance between pruning cuts (Dcuts).

TABLE 2. Detailed characterisation of the total plots (*n* = 80): Comparison between the registered age and the analysis of historical aerial photography. (part 1/2)

			Information from aerial photography			
ID	*Registry ID	Registered age	Training system	Spatial pattern	Distance between rows (m)	Age range
1	6-45-120.124	42	Gobelet	Marco real	2,0	> 48
2	6-46-64	6	Trellis		3,0	4-7
3	55-41-6.77.78	52	Gobelet	Tresbolillo	2,0	> 48
4	55-42-162.168	6	Trellis		3,0	4-7
5	114-18-58	47	Gobelet	Marco real	2,0	> 40
6	114-18-183	9	Trellis		3,0	7-10
7	154-24-78	82	Gobelet	Tresbolillo	2,0	> 48
8	154-24-79	11	Trellis		3,0	10-13
9	252-35-176	3	Trellis		3,0	1-4
10	252-35-129	3	Trellis		3,0	1-4
11	252-35-170	42	Gobelet	Marco real	2,0	> 40
12	252-35-122	3	Trellis		3,0	1-4
13	3-7-39	23	Trellis		3,0	16-19
14	6-45-31	29	Trellis		3,0	19-26
15	6-36-143	34	Trellis		3,0	> 48
16	6-26-39	26	Trellis		3,0	19-26
17	6-23-1	14	Trellis		3,0	13-16
18	6-19-22	21	Trellis		3,0	19-26
19	6-37-27	3	Trellis		3,0	1-4
20	6-34-24	5	Trellis		3,0	4-7
21	6-40-55	8	Trellis		3,0	4-7
22	55-60-86	21	Trellis		3,0	16-19
23	6-40-13	30	Trellis		3,0	4-7
24	6-33-94	30	Trellis		3,0	4-7
25	6-36-140	3	Trellis		3,0	1-4
26	10-11-1	21	Trellis		3,5	16-19
27	27-6-333.334.335.1	83-73	Gobelet	Tresbolillo	2,0	> 48
28	27-6-35	53	Gobelet	Tresbolillo	2,0	> 48
29	27-11-110	48	Trellis		2,5	> 48
30	55-36-135	21	Trellis		3,0	16-19
31	55-36-51	10	Gobelet	Marco real	2,5	7-10
32	55-41-46	27	Trellis		2,5	19-26
33	55-41-28	21	Trellis		3,0	16-19
34	55-41-48	58	Gobelet	Marco real	2,0	19-26
35	55-42-179	7	Trellis		3,0	4-7
36	55-43-13	16	Trellis		3,0	13-16
37	55-59-83	21	Trellis		3,0	16-19
38	55-60-84	21	Trellis		3,0	16-19
39	55-61-149	17	Trellis		3,0	13-16

*In the 'Registry ID' column, the numbering corresponds to the identification codes for the municipality, polygon, and plot of each vineyard.

TABLE 2. Detailed characterisation of the total plots (*n* = 80): Comparison between the registered age and the analysis of historical aerial photography. (part 2/2)

40	55-61-25	14	Trellis		3,0	10-13
41	55-63-19	33	Gobelet	Marco real	2,0	> 48
42	55-64-37	15	Trellis		3,0	13-16
43	55-66-146	19	Trellis		3,0	16-19
44	55-67-7.8	63	Gobelet	Tresbolillo	2,0	> 48
45	55-67-22	21	Trellis		3,0	16-19
46	55-67-27	18	Trellis		3,0	16-19
47	55-67-35	8	Trellis		3,0	7-10
48	55-68-36.35.39	8	Trellis		3,0	4-7
49	55-68-38	8	Trellis		3,0	7-10
50	60-30-293	63	Gobelet	Tresbolillo	2,0	> 48
51	61-11-265	5	Trellis		3,0	4-7
52	61-11-33	3	Trellis		3,0	1-4
53	114-1-239	7	Trellis		3,0	4-7
54	114-2-159	30	Trellis		3,0	19-26
55	114-3-111	30-29	Gobelet	Marco real	2,3	19-26
56	114-4-463	27-26	Trellis		3,0	19-26
57	114-4-465	19	Trellis		3,0	16-19
58	114-6-214	15	Trellis		3,0	13-16
59	114-11-43	11	Trellis		3,0	7-10
60	114-18-234	3	Trellis		3,0	1-4
61	114-18-269	73	Gobelet	Marco real	2,5	> 48
62	114-23-304	9	Trellis		3,0	7-10
63	114-25-310.311	18	Trellis		3,0	16-19
64	114-25-322	6	Trellis		3,0	4-7
65	114-29-29	8	Trellis		3,0	4-7
66	114-32-3	19	Trellis		3,0	16-19
67	114-502-118	26	Trellis		3,0	19-26
68	114-503-112	29	Trellis		3,0	19-26
69	154-5-217	42	Trellis		3,0	> 48
70	154-9-1348	5	Trellis		3,0	16-19
71	154-18-165	48	Trellis		3,0	16-19
72	154-22-17	42	Trellis		2,0	16-19
73	154-22-68.99	78-73	Gobelet	Marco real	2,0	> 48
74	154-41-57	73	Gobelet	Marco real	2,0	> 48
75	217-503-2	12	Trellis		3,0	10-13
76	252-2-2.3	34	Gobelet	Marco real	3,0	19-26
77	252-55-87	47	Gobelet	Marco real	2,2	> 48
78	252-57-83	32	Trellis		2,0	16-19
79	114-35-150	8	Trellis		3,0	4-7
80	114-2-201.204	35	Gobelet	Marco real	2,0	> 28

*In the 'Registry ID' column, the numbering corresponds to the identification codes for the municipality, polygon, and plot of each vineyard.

with a *marco real* pattern. Finally, in terms of row spacing, the data indicate that in plots with wider rows (3 to 3.5 m), the mean age decreases compared to plots with narrower rows (2 to 2.5 m).

2. Results from the morphological study of the vines

The morphological study conducted on a sub-sample of 14 vineyards is presented in Table 3. The results, expressed as mean ± standard deviation to reflect in-plot variability, indicate that the total vine length, measured from the base to the final pruning cut, ranges from 48 cm to 120.4 cm (with standard deviations ranging from 3.42 to 13.64 cm). Regarding annual growth rates, the calculated values for each vineyard vary between 1 and 2.09 cm per year (with standard deviations from 0.15 to 0.67 cm/year), resulting in a regional mean growth rate of 1.6 cm. However, to accurately reflect local conditions, the specific growth rate (G_{vine}) of each plot was used to estimate its morphological age, corresponding to the column "Morphological study".

Regarding the comparison of the three age data sources. In vineyards 5, 7, and 80, the morphological estimates limited the open age ranges from aerial photography and are higher than the registered age. In plots 50 and 74, the morphology is between the registered age and aerial range. For vineyard 11, all three age sources show a high degree of coincidence. In the remaining cases, the age estimates through morphological data are lower than those provided by either the official registers or the aerial photography analysis.

3. Results from varietal and rootstock identification

The results of the plant material identification conducted across the sub-sample of 14 vineyards selected for their high longevity are presented in Table 4. The collected samples were categorised into dominant and sporadic, based on the frequency observed during field prospections.

Regarding the rootstock identifications, Rupestris du Lot was found to be the predominant variety, representing the dominance in 12 of the 14 studied plots. In the remaining two plots, the majority of rootstocks identified were Richter 110 (Plot 11) and Millardet et Grasset 41 B (Plot 80). In terms of sporadic rootstocks, a diverse range was recorded, with Ganzin 1 being the only variety identified in more than one plot (Plots 28 and 61). Other secondary rootstocks identified include Richter 31, Couderc 3306, Paulsen 1103, and Millardet et Grasset 141A.

Concerning the scion identifications, the presence of Grenache was hegemonic, appearing as the dominant variety in 100 % of the analysed plots. Among the secondary cultivars, Muscat à Petits Grains Blancs was the most frequent, appearing sporadically in two plots (Plots 44 and 50). Other traditional varieties identified in specific locations include Gallera Roja, Rojal Tinta, Jarrosuelto, Viura, and Quiebratinajas.

The results of the varietal identifications for the control plots are presented in Table 5. In this subset, the rootstocks identified as the dominant show a clear change compared to the initial 14-vineyard study. Richter 110 arose as the predominant rootstock, appearing in 4 of the 6 control plots, whereas it had only been recorded once as a dominant rootstock in the previous analysis of 'old vineyards' (Table 4). Ruggeri 140 and Millardet et Grasset 41B appeared in the remaining control plots as their primary rootstocks. Regarding sporadic presence, only Richter 110 was identified as a secondary variety in one instance.

In contrast to the rootstock variability, the scion identifications demonstrate absolute consistency with the previous findings. Grenache remained the hegemonic variety, representing the dominant scion in 100 % of the control plots. Also, unlike the vineyards selected for their longevity, no sporadic varieties were detected within these control samples.

The dominant rootstocks identified in Tables 4 and 5 have been categorised into three age ranges to evaluate their distribution patterns (Figure 5). The data reveals a notable change in the choice of plant material over time. In the youngest vineyards (< 25 years), the rootstock identified was composed mainly of Richter 110, and secondary of Millardet et Grasset 41 B, and Ruggeri 140. As the age of the vineyards increases, the presence of these varieties decreases significantly. In the intermediate group (35–55 years), each of these modern rootstocks represents only 12.5 % of the total, as the dominant of these vineyards were established on Rupestris du Lot. Finally, in the oldest age group (> 60 years), Rupestris du Lot becomes the unique primary rootstock.

DISCUSSION

The comparative analysis between the official P.D.O. Campo de Borja records and the historical aerial photographs demonstrates a notable degree of correspondence. By applying an uncertainty margin of ± 3 years, the age ranges from the aerial photographs coincide with the registered ages in 78.75 % of the cases, and if this margin is increased to ± 5 years, the success rate rises to 83.75 %. This high level of agreement is closely related to the prevalence of trellis systems in the sample, since these are relatively modern plantations, given that their use was officially approved following the publication of the Order of 18 November 1992 (Ministerio de Agricultura Pesca y Alimentación, 1992), so their administrative documentation tends to be more precise and easier to verify through recent aerial photographs. For the remaining plots where the official age was older than the range established via aerial photographs analysis, a difference of approximately 20 years was identified, suggesting a possible uprooting and replanting process during that interval, which might not have been included in the official registry, still reflecting the age of the original vineyard rather than the current plantation. Finally, there are cases where plots were identified as older than recorded in the P.D.O. registers, highlighting the capacity of diachronic aerial studies to prove that certain vineyards were already established prior to their official registration date, which reflects gaps in some official documentation.

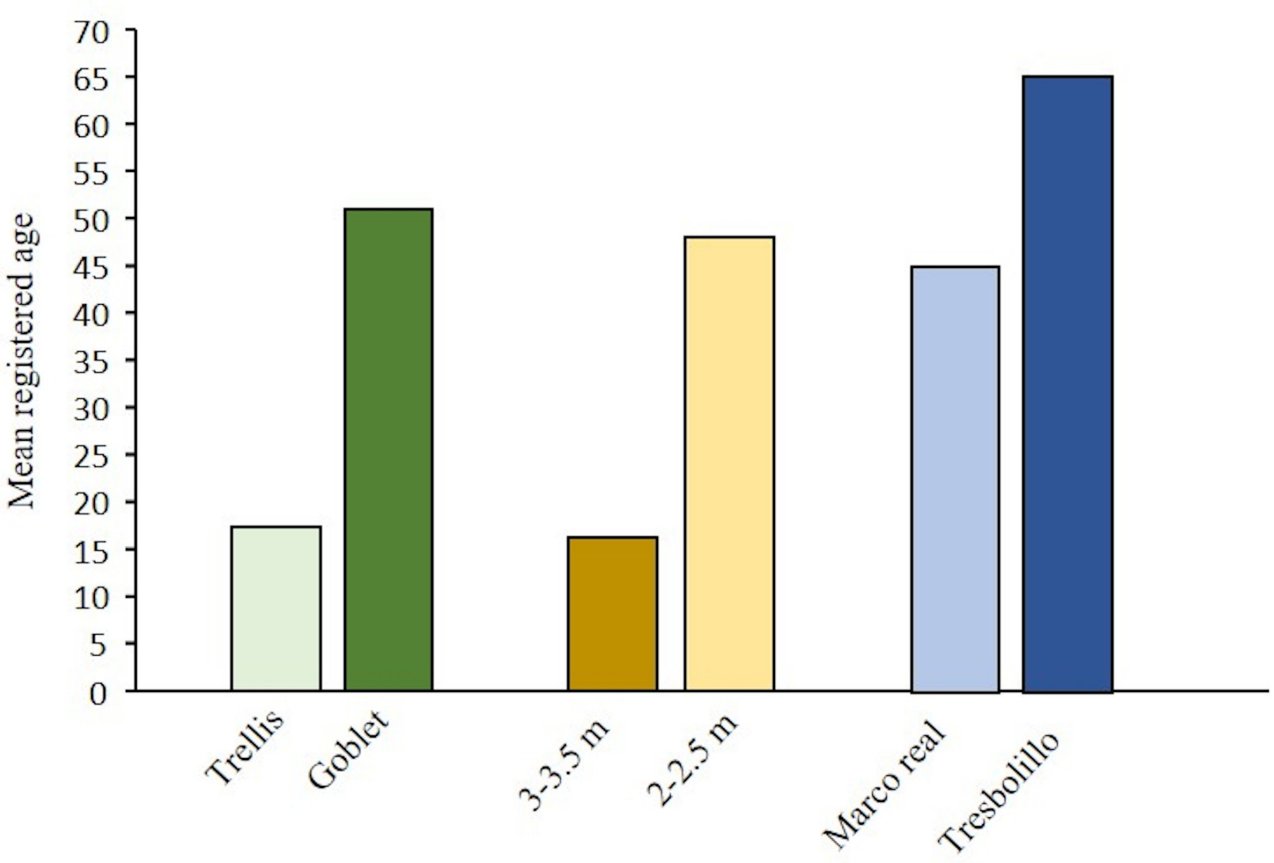


FIGURE 4. Mean registered age of the vineyards according to training system, spatial pattern, and row distance.
*Marco real and tresbolillo vineyards correspond to the goblet training system.

TABLE 3. Morphological parameters (mean ± standard deviation) and comparative age assessment based on official registered, aerial photography, and morphological study, for the vineyard sub-sample (*n* = 14).

			Age/ Age range		
ID	Lt (cm)	G_{vine} (cm/year)	**Registered age**	**Aerial photography**	**Morphological study**
1	92.6±4.67	2.09±0.41	42	> 48	44
3	60.5±7.23	1.41±0.24	52	> 48	43
5	93.4±13.33	1.82±0.32	47	> 44	51
7	120.4±11.78	1.32±0.21	82	> 48	91
11	70.0±12.91	1.67±0.27	42	> 44	42
27	56.0±13.64	2.07±0.44	83-73	> 48	27
28	49.8±8.04	1.60±0.43	53	> 48	31
29	48.0±3.42	1.57±0.55	48	> 48	31
44	66.4±5.94	1.66±0.55	63	> 48	40
50	55.6±4.67	1.14±0.31	63	> 48	49
61	55.0±5.12	1.60±0.15	73	> 48	34
74	67.0±6.96	1.00±0.27	73	> 48	67
77	64.2±7.36	1.68±0.67	47	> 48	38
80	85.9±9.75	1.93±0.31	35	> 28	45

TABLE 4. Results of the scion and rootstock identification analysis for the selected sub-sample (*n* = 14).

	Rootstock		Scion	
ID	Dominant	Sporadic	Dominant	Sporadic
1	Rupestris du Lot		Grenache	
3	Rupestris du Lot	Richter 31	Grenache	
5	Rupestris du Lot		Grenache	
7	Rupestris du Lot	Couderc 3306	Grenache	
11	Richter 110		Grenache	
27	Rupestris du Lot		Grenache	Gallera Roja
28	Rupestris du Lot	Ganzin 1 Paulsen 1103	Grenache	Rojal Tinta Jarrosuelto
29	Rupestris du Lot		Grenache	
44	Rupestris du Lot		Grenache	Muscat P. Grains
50	Rupestris du Lot	Unidentified	Grenache	Muscat P. Grains Viura
61	Rupestris du Lot	Ganzin 1	Grenache	
74	Rupestris du Lot		Grenache	Quiebratinajas
77	Rupestris du Lot	141 A Mill. Grasset	Grenache	
80	41B Mill. Grasset		Grenache	

TABLE 5. Results of the scion and rootstock identification analysis for the control sub-sample (*n* = 6).

	Rootstock		Scion	
ID	Dominant	Sporadic	Dominant	Sporadic
2	Ruggeri 140	Richter 110	Grenache	
4	41 B Mill. Grasset		Grenache	
6	Richter 110		Grenache	
8	Richter 110		Grenache	
12	Richter 110		Grenache	
79	Richter 110		Grenache	

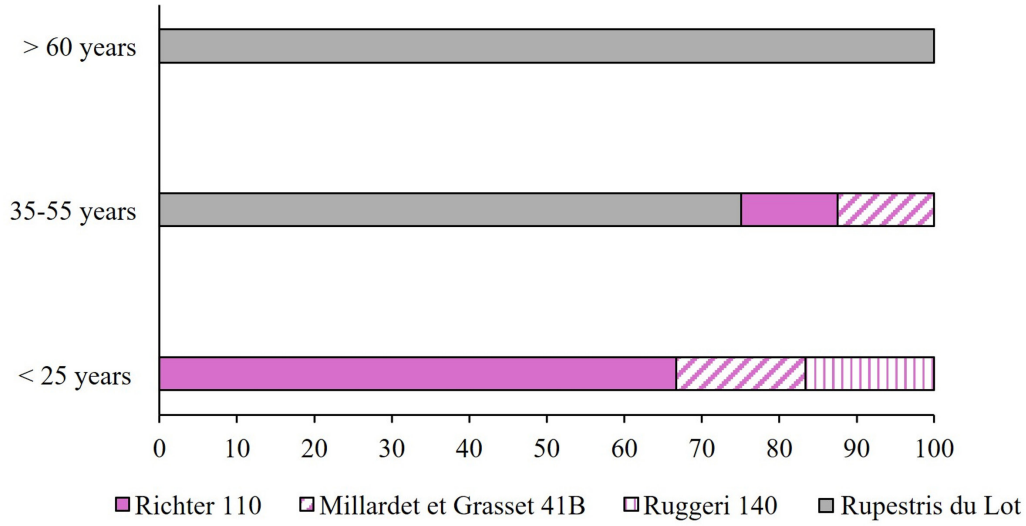


FIGURE 5. Estimation of the distribution of dominant rootstocks across the three main age groups.

Between the training system and the distance between rows, a direct correlation is observed, where trellis systems and row distances of 3–3.5 m show similar mean ages, and a similar trend is found between goblet systems and row distances of 2–2.5 m. It is worth noting that the slight variation within these groups could be related to vineyard conversion processes, where traditional goblet vineyards were adapted to trellis systems. The age difference between these two groups, which exceeds 30 years, is supported by Hidalgo and Fernández-Cano (2011), who detail that traditional Spanish planting patterns were based on *marco real* and *tresbolillo* configuration. Regarding the spatial pattern of goblet vines, the data show that the majority of old vineyards are those established in a *tresbolillo* pattern. This suggests a chronological transition in the viticulture practices of the studied area, beginning with the *tresbolillo* configuration, moving to the *marco real* pattern, and finally transitioning to the modern trellis system. As noted by Hidalgo and Fernández-Cano (2011), this transition was driven by the mechanisation of the sector, establishing wider rows to accommodate agricultural machinery. While the *marco real* system allowed for increased row distance while reducing the distance between vines within the same row, therefore preserving a rectangular layout compatible with machinery, the *tresbolillo* system was gradually abandoned due to its geometric complexity for agricultural machinery.

The morphological study revealed a standardised regional growth rate of 1.6 cm/year in the evaluated plots. This low rate is consistent with the pattern of slow development and restricted growth expected for the Grenache variety under the characteristic water-stress conditions of the Campo de Borja continental climate. This finding is supported by dendrochronological studies in the region, which demonstrate that the radial wood growth of *Vitis vinifera* is also severely limited by water availability in these zones (Camarero *et al.*, 2024). The application of this morphological methodology has proven instrumental in refining the age ranges initially estimated via aerial photographs. At the same time, the study identified cases where the estimated morphological age exceeds the official P.D.O records, suggesting that certain administrative documentation may be insufficient for a detailed analysis. In the remaining cases, the morphological study produced age estimates lower than those obtained from either aerial photographs or official registers. Since our targeted sampling strategy avoided co-planted vines, these lower values are not attributed to vine renovation. Instead, these lower values likely reflect the accumulation of pruning scars over the years, which can sometimes hide the total measurable length of the vine. Despite these limitations, the integration of morphological data with historical photographs and registers provides a robust framework to verify the longevity of the region's viticulture heritage.

The analysis of the plant material shows a historical trend in the selection of rootstocks within the studied area. The findings indicate that the most long-lived vineyards present Rupestris du Lot as the dominant rootstock. This uniformity underscores the heritage value of these parcels, as Rupestris du Lot was one of the first successful rootstocks developed after the phylloxera crisis in 1879. In contrast, the control plots are characterised by contemporary rootstocks such as Richter 110, Ruggeri 140, and Millardet et Grasset 41B, which are the most widely used in current viticulture (Marín *et al.*, 2021). On the other hand, in the intermediate group (35–55 years), while Rupestris du Lot continues to predominate, modern rootstocks begin to emerge, representing the transition within the region.

Regarding the scion analysis, the results confirm the absolute hegemony of the Grenache variety across all age groups. This strengthens the status of Grenache as the dominant cultivar in Campo de Borja. Remarkably, younger vineyards show a total absence of secondary varieties, whereas other scions appear in the most long-lived plots, such as Muscat à Petits Grains Blancs, Viura, or Quiebratinajas, often found at the vineyard margins. This varietal diversity in older vineyards aligns with findings from other historical wine-growing regions (Urrestarazu *et al.*, 2015) and reaffirms the role of long-lived vineyards as reservoirs of plant material.

To conclude, the multidisciplinary model developed provides an objective, non-invasive, and reproducible framework for the certification and valorisation of Grenache viticulture heritage in the P.D.O. Campo de Borja. This methodology is directly transferable to other similar regions such as La Rioja or Navarre and may require adjustments to be used in other areas interested in managing their 'old vineyards'. Furthermore, it validates the need to implement objective classification methods aligned with OIV international standards.

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