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1 **Carbon isotope discrimination as a surrogate for**
2 **Soil Available Water Capacity in rainfed areas: A study in the Languedoc Vineyard**
3 **plain**

4
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9 **Highlights**

10
11 Four contrasting years were monitored to investigate different soil water conditions.
12 The Soil Available Water Capacity (SAWC) was measured on 21 sites.
13 The integrated relationship between the mean of $\delta^{13}\text{C}$ and SAWC was successfully tested.
14 $\delta^{13}\text{C}$ of grapes can be considered as a simple and inexpensive surrogate for determining
15 SAWC.

16
17
18 **Abstract**

19 Soil available water capacity (SAWC) is a key soil function for plant growth. Classical SAWC
20 characterization requires time consuming determinations of bulk density and specific soil
21 moisture contents. Consequently, these data are extremely sparse in existing soil databases.
22 Using surrogates of the vegetal response to characterize SAWC across a great number of
23 sites constitutes a promising perspective. The carbon isotope ratio ($\delta^{13}\text{C}$) measured in a
24 plant organ is largely known as an indicator of plant water status. The aim of the paper is to
25 test $\delta^{13}\text{C}$ as an indicator of SAWC in rainfed vineyard.
26 $\delta^{13}\text{C}$ values of grapes at harvest time were measured at 21 sites on the Languedoc vineyard
27 plain with contrasting SAWC (33 to 308 mm) for four years (2015 to 2018) with contrasting
28 annual precipitation (from 390 to 715 mm). The relationships between $\delta^{13}\text{C}$ and SAWC

29 determined using a classical approach (soil description, soil sampling and laboratory
30 methods) were satisfactory for all years (RMSEs from cross validation were between 35 and
31 61 mm). Better relationships were obtained between $\delta^{13}\text{C}$ and SAWC for years that showed
32 a full winter recharge of SAWC (2015, 2017 and 2018). Averaging the $\delta^{13}\text{C}$ measurements
33 over such years provided an even better relationship ($R^2=0.85$; RMSE 32 mm), which was
34 successfully validated in distant sites on the Languedoc vineyard plain.

35 This work demonstrated that $\delta^{13}\text{C}$ can be considered as a simple and inexpensive surrogate
36 for estimating SAWC. In addition to considerably increasing the density of SAWC
37 measurements, the use of $\delta^{13}\text{C}$ would lead to better consideration of the contribution of deep
38 horizons in the case of perennial plants. Application of this isotopic technique to other agro-
39 systems is required to better define the potential areas of use of $\delta^{13}\text{C}$.

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43 **1. Introduction**

44

45 Soil available water capacity (SAWC) or soil available water holding capacity (AWHC) is a
46 well-known concept that has been used for a long time to express the capacity of soils to
47 store water for plants (Veihmayer and Hendrickson, 1927). It has been demonstrated that
48 SAWC is one of the most important soil factors for plant growth and that it influences
49 photosynthesis rate, carbon allocation, and nutrient cycling (Lebourgeois et al., 2005; Breda
50 et al., 2006). It is therefore a first order parameter that is used in crop modelling (Brisson et
51 al., 1998), land evaluation and, recently, soil ecosystem service assessment (Dominati et al.
52 2014).

53 Determining the SAWC requires costly and time-consuming measurements of soil properties.
54 Bulk density and volumetric water content at wilting point and field capacity require
55 undisturbed sampling and physical measurements in the laboratory (Klute, 1986; Bruand and
56 Tessier, 2000). Moreover, determination of the SAWC for perennial plants having a deep root

57 system requires investigation of the deep horizons, which are not always accessible.
58 Consequently, the SAWC data are extremely sparse in existing soil databases, which
59 prevents the use of these databases as inputs for Digital Soil Mapping approaches
60 (McBratney et al., 2003) as is currently done for other more current soil properties (e.g.,
61 Organic Carbon, textural fractions). To overcome this problem, pedotransfer functions (Rawls
62 et al., 1982; Al Majou et al., 2008) can be used to estimate the specific water content from
63 available soil properties, which has allowed the production of SAWC maps (Leenaars et al.,
64 2018, Dobarco et al., 2019). However, these functions convey a great amount of uncertainty
65 that could generate significant errors in SAWC maps (Dobarco et al., 2019). Therefore, the
66 increase in well-characterized sites with regard to SAWC is a prerequisite for a significant
67 improvement of SAWC maps.

68 Using surrogates of the vegetal response to characterize SAWC across a great number of
69 sites is a promising perspective. Remote sensing approaches that involve vegetation indices
70 have been proposed. For example, Araya et al. (2016) proposed to directly test the multi-
71 date Normalized Difference Vegetation Index as a surrogate for the dynamic response of
72 plants to soil functions, especially SAWC. A relationship between evapotranspiration-based
73 covariates extracted from ASTER satellite imagery and soil depth, a first order parameter for
74 SAWC calculation, was found in vineyards (Taylor et al., 2013).

75 In the same way, the carbon isotope ratio ($\delta^{13}\text{C}$) is largely known as an indicator of plant
76 water status and has been tested on different species such as wheat (Merah et al., 2001),
77 conifers (Warren et al., 2001), and vineyards (Gaudillère et al., 2002). In the case of
78 vineyards, many studies have demonstrated the linear relationships between $\delta^{13}\text{C}$ measured
79 in berries at harvest and the minimal values of pre-dawn leaf water potential during ripening.
80 Van Leeuwen et al. (2001) measured the $\delta^{13}\text{C}$ in berries from 9 closed vineyards with
81 different soils during contrasted years. They found a linear relationship between $\delta^{13}\text{C}$ and the
82 minimal values of pre-dawn leaf water potential during ripening ($R^2= 0.81$). The soils and the
83 years explained a large part of the variance. Gaudillère et al. (2002) found a linear
84 relationship in case of various grapevine genotype (e.g. Cabernet Sauvignon, Cabernet

85 Franc and Merlot). They also tested 31 grapevine varieties within a same growing condition
86 and they measured $\delta^{13}\text{C}$ values from -21.6 (Riesling) to -24.9 (Muscat). However, 24
87 varieties ranged between -22.5 and -23.8. Gomez-Alonso and Garcia-Romero (2010) found
88 lower differences between 8 varieties in a same growing condition, from -20.5 (Airen) to 21.6
89 (Sauvignon blanc). Santesteban et al. (2015) reviewed the $\delta^{13}\text{C}$ datasets from the literature
90 and proposed $\delta^{13}\text{C}$ threshold values that correspond to significant differences in vineyard
91 water status during the ripening period.

92 The low cost of $\delta^{13}\text{C}$ measurements that allows the collection of large samplings was
93 exploited in some studies. A large set of $\delta^{13}\text{C}$ measurements was used to produce a spatial
94 model of vine water status at the plot scale (Herrero-Langreo et al., 2013). Some studies
95 focused on the use of $\delta^{13}\text{C}$ as an indicator of functional parameters in relation to vine water
96 status. Guix-Hebrard et al. (2007) used measured $\delta^{13}\text{C}$ for revealing the influence of water
97 table depth on the grape maturation. Van Leeuwen et al. (2018) considered $\delta^{13}\text{C}$ as a high-
98 resolution tool among a set of indicators for characterizing vineyard terroirs. Costantini et al.
99 (2010) delineated the Sangiovese terroir with a combination of proximal soil sensing and the
100 measurement of $\delta^{13}\text{C}$ in Sangiovese wines.

101 However, to our knowledge, $\delta^{13}\text{C}$ measurements have still not been correlated with SAWC
102 measurements. The vine water status via the predawn leaf water potential is known to be
103 correlated to the fraction of transpirable soil water (FTSW) (Pellegrino et al., 2004), which,
104 during the driest growing seasons, may be considered as a surrogate for SAWC in rainfed
105 areas. Therefore, a relationship between easily accessible $\delta^{13}\text{C}$ measurement and the
106 SAWC is conceivable. Moreover, in the case of vineyards, the roots of grapevines are
107 generally established throughout the entire horizons of soils, except for the limiting specific
108 conditions (hydromorphic horizons, cemented horizons or C horizons with chemical or
109 physical limitations), despite the high dependence of grapevine rooting patterns on the
110 rootstock.

111 The aim of this paper is to directly test $\delta^{13}\text{C}$ measured in vineyards at the harvest time as a
112 surrogate of a large range of measured SAWCs in different soils of the Languedoc area.

113 Four years were monitored to investigate different soil water conditions during the growing
114 seasons of the vineyards.

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116 **2. Materials and methods**

117

118 2.1 Study areas

119

120 The 21 sites that constitute the experimental dataset of this study were located in two study
121 areas, both included in the vineyard plain of Languedoc in southern France (figure 1). The
122 first study area is the Peyne River catchment which includes 13 sites. The second one is
123 located near Narbonne close to the sea and includes 8 sites. The elevation ranges from 5 m
124 (Pech Rouge) to 340 m (northwest of the Peyne area). The landscape has gentle landforms.
125 The grapevine varieties and the agricultural practices are representative of the region. The
126 precipitation conditions were monitored during 25 years both in the Peyne catchment and in
127 Pech Rouge station. The annual precipitation of 628 mm for the Peyne catchment and 562
128 mm for the Pech Rouge station are unevenly distributed throughout the year, with major
129 precipitation occurring in autumn and spring. The annual reference evapotranspiration is
130 1109 mm. The mean maximum temperature is approximately 15°C in January and 30°C in
131 July/August. The catchments present a typical Mediterranean hydrological response, with the
132 potential annual water storage mainly dependent on the annual precipitation and the
133 occurrence of extreme runoff events, which are not favourable for the water infiltration.
134 Therefore, the annual water balance highly varies between years.

135 The soil pattern of the Peyne catchment arises mainly from variations in lithology, and the
136 main soil characteristics depend on the type of parent material (figure 1). The entire valley is
137 underlain by heterogeneous Miocene marine calcareous sandstone and lacustrine limestone,
138 which form the parent material of several types of soil, including calcaric leptosols, calcaric
139 regosols, and calcisols (IUSS working group WRB, 2015). These Miocene sediments are
140 partly overlain by successive alluvial deposits ranging from Pliocene to Holocene, and they

141 differ in their initial nature and in the duration of weathering conditions. Therefore, these
142 sediments have produced intricate soil patterns that include a great range of soil types such
143 as calcisols, endogleyic calcisols, luvisols (chromic), and fluvisols. Recent volcanic activity
144 and local transport of colluvium material along slopes have added to the complexity of the
145 soil pattern. Consequently, the soils of the valley present contrasting characteristics in terms
146 of texture, stoniness and soil depth, which determine their SAWC.

147 The second study area corresponds to the experimental station of INRA Pech Rouge located
148 in the “La Clape” massif, a small Pyrenean thrust sheet composed of Cretaceous marine
149 deposits. Contrasting sites were chosen among different available SAWCs. The main soils
150 were developed over interbedded micritic limestones and orbitolina clayey limestones. The
151 soils were generally thin over the limestones, with a high content of coarse fragments
152 (Leptosols). In the bottom part of the fields, there were important accumulations of
153 sediments, and the soil depth increased (Calcisols).

154

155 *<Figure 1 here>*

156

157 2.2 Site sampling

158 The sites were chosen to be representative of the diversity of soil characteristics, especially
159 soil depth and SAWC (table 1 and figure 1). A total of 13 sites were located in the Peyne
160 catchment to calibrate the relations, and 8 additional sites were located in the Pech Rouge
161 INRA station to validate the relations with independent sites. A site corresponds to
162 approximately 15 m² (9 vines) within the vineyards to limit the spatial variability of soil
163 properties and assign a SAWC to a site with a maximum of precision. Regarding
164 agronomical aspects, the vineyards were chosen (i) to be representative of the regional
165 vineyards and (ii) to avoid the situations where the relation between the SAWC and the vine
166 water status may be disturbed (e.g., irrigated zones; young vineyards with insufficient root
167 systems). The vineyards were 15-20 years old and without irrigation. The plantation density
168 (4000 plants/ha), the trellising (2 stages), the pruning system (double cordon) and the

169 number of buds (16 to 20) were the same at all sites. However, the variety differed, with
170 Syrah (sites 6,9), Cabernet Sauvignon (sites 4,10,18), Sauvignon blanc (site 14), Grenache
171 noir (site 5,8), and Merlot (sites 2,3,7,11,12).

172

173 2.3 Soil survey

174

175 Soil pits were dug near each selected site during the winter of 2016 and the soil
176 morphological parameters were observed in the field (soil depth, structure, colour, stones,
177 roots abundance) according to the guidelines for soil description (FAO, 2006). The soil
178 horizons were determined in relation to these descriptions, and bulk densities (ρ_b) were
179 measured by core sampling with 100 cm³ stainless-steel cylinders (Blake and Hartge, 1986)
180 with 6 replicates per horizon. ρ_b was determined as the ratio between the dry soil mass and
181 the total core sampling volume. Moreover, each sample was sieved to extract the coarse
182 fragments (e.g. >2mm), and the bulk density of the fine earth (ρ_{bFE}) was determined as the
183 ratio between the dry soil mass without the coarse fragments and the total core sampling
184 volume without the volume corresponding to the coarse fragments. This volume was
185 calculated from the mean bulk density of the coarse fragments (ρ_{bCF}) according to the type of
186 pebbles already measured in the Payne catchment and in Pech Rouge station (e.g. old
187 alluvial pebbles 2.8 and limestone 2.5). Undisturbed soil samples of over 500 g were taken in
188 each horizon for characterisation of the specific water retention at -33 kPa (field capacity)
189 and -1500 kPa (wilting point) according to the pressure chamber method (Klute, 1986).
190 Disturbed soil samples localized in the same horizons were used for classical texture and
191 coarse-fragment analysis. The samples were sieved to separate pebbles greater than 2 mm
192 in diameter from the fine earth. The particle size distribution was analysed following the
193 destruction of organic matter and dispersion with sodium hexametaphosphate (AFNOR, N
194 FX 31-107). The clay (< 2 μ m) and silt (2-50 μ m) contents were quantified by sedimentation,
195 and sand (50-2,000 μ m) was measured via sieving. The detailed results of the soil survey are
196 summarized in Table 1.

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2.4 Soil available water capacity (SAWC)

The SAWC of each horizon was calculated based on equation (1). The morphological variables that impact the rooting were taken into account for the calculation of the actual SAWC. In the case of low content of coarse fragments (<10%), their contributions to the SAWC were neglected. However, in the case of high content of coarse fragments (Pech Rouge sites), additional SAWCs were calculated from the water content measured within the coarse fragments (Tetegán et al., 2011). Considering that the 15-20 year-old studied vineyards had sufficient time to develop their root system, horizons without living roots did not contribute to the SAWC. The different causes were examined. Site 2 presented a deep horizon (1.95 - 2.70 m) without roots due to (i) seasonal waterlogging within the horizon and (ii) vertic properties not suitable for roots. Site 4 presented a large soil depth but the deep horizons were temporary waterlogged, and no roots were observed. Horizon C of site 8 presented a high content of powder of calcium carbonate, and no roots were observed. The calculation of SAWC and general soil data are given in Table 1.

$$SAWC = \sum_{horizon=1}^n (Z_{(horizon)} \times (W_s - W_r) \times \rho_{bFE} \times \left\{ 10 - \frac{CF \times \rho_b}{10 \times \rho_{bCF}} \right\})$$

Where :

- SAWC (mm) total soil available water capacity
- n number of actual horizon
- Z_(horizon) (m) thickness of the horizon
- W_s * mass water content at 0.33 bar
- W_r* mass water content at 15 bar
- CF (%) * mass proportion of coarse fragments
- ρ_b bulk density
- ρ_{bFE} bulk density of the fine earth
- ρ_{bCF} bulk density of coarse fragments
- *each property was analysed for each actual horizon

<Table 1 here>

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2.5 $\delta^{13}\text{C}$ sampling and analysis

A total of 100 berries were collected at the harvest time from the 9 vines at each site during 4 successive years (2015- 2018) for the Payne sites. The sampling dates varied between the 25th August (2016), and the 10th September (2015), depending on the vine variety and the climate of the year. The samples for the Pech Rouge site were collected only in 2018. The samples were ground at the laboratory, and 2 ml samples were centrifuged and oven dried. The resulting powder was analysed by a continuous-flow isotope ratio mass spectrometer (ISOPRIME, GV Instruments, Manchester). $\delta^{13}\text{C}$ values are expressed with reference to the PeeDeeBelemnite (PDB) standard (Farquhar et al., 1989). In the case of grapevines, Santesteban et al. (2015) proposed a correspondence between $\delta^{13}\text{C}$ and the water deficit via the vine water status measured in a set of studies. The water deficit is considered as weak or null with $\delta^{13}\text{C}$ lower than -26‰; conversely, the water deficit is severe with a $\delta^{13}\text{C}$ higher than -24‰.

2.6 Experimental protocol

The Payne sites were first chosen to calibrate the relationship between $\delta^{13}\text{C}$ and SAWC at the site scale. The relationships were separately analysed for each successive year to enable discussion of the results according to the specificity of each vintage. A classical leave-one-out cross validation was applied to validate the relationship on the Payne sites for each year.

Three years (2015, 2017 and 2018) were chosen to calculate the $\delta^{13}\text{C}$ mean for each site within the Payne catchment and calibrate a new multivariate relationship between $\delta^{13}\text{C}$ and SAWC. This relationship was validated with the independent Pech Rouge sites using classical figures-of-merit, coefficients of determination (R^2) and Root Mean Square Errors (RMSE).

263 **3. Results**

264

265 *3.1 Precipitation*

266 The four years exhibited large variations of annual precipitation in the Payne catchment
267 (figure 2). Only the 2015 precipitation was close to the 25-year average precipitation. The
268 2016 precipitation was largely below this average. 2017 and 2018 precipitations exceeded
269 the 25-year average precipitation. Although the 2017 growing season was the driest among
270 the four years, most of the 2017 precipitation events occurred before bud break and secured
271 the soil water storage. The precipitations during 2018 in Pech Rouge station were also upper
272 than the 25-year average precipitation.

273 *<Figure 2 here>*

274

275 *3.2 $\delta^{13}\text{C}$*

276 The $\delta^{13}\text{C}$ mean results from the Payne site showed significant differences between years
277 (Table 2). The ranges of values are in accordance with those found by Guix et al. (2007)
278 within the same region. As expected, the driest year (2016) presented a significantly higher
279 $\delta^{13}\text{C}$ mean and the highest maximum value. However, the minimum value measured in 2016
280 was comparable to that in the other years. The years 2017 and 2018 had lower $\delta^{13}\text{C}$ values.
281 The $\delta^{13}\text{C}$ measured values in the Pech Rouge sites during 2018 were significantly higher
282 than those measured in the Payne sites.

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284 *<Table 2 here>*

285 *3.3 Relationship between $\delta^{13}\text{C}$ and SAWC*

286 The linear relationships between SAWC and $\delta^{13}\text{C}$ were significant for the Payne sites
287 regardless of years (Figure 3). The increase of $\delta^{13}\text{C}$ always corresponded to a decrease of
288 SAWC. Regarding the cross validation, the year 2015 presented the lowest errors of
289 prediction, which were of the same order of magnitude as the errors of the local
290 determinations of SAWC from field laboratory measurements.

291

292 <Figure 3 here>

293 The errors were more important in 2017 and 2018, although the general trend was
294 conserved. Conversely, the relationship during the year 2016 was different. $\delta^{13}\text{C}$ values
295 corresponding to sites with a medium SAWC (100 -200 mm) increased, particularly for sites
296 6,8,10,18. The sites with high (11,12) or low (3,5) SAWC had a relative stability through the
297 years. Regarding the trend of the relationship, the measured $\delta^{13}\text{C}$ for site 5 was always lower
298 than expected.

299

300 <Figure 4 here>

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302 For each site, the means of $\delta^{13}\text{C}$ measured during 2015, 2017 and 2018 were calculated and
303 compared with the SAWCs (figure 4). The new calibration over the Payne sites during the
304 three years presented better figures of merit than each separated year. Moreover, the
305 successful validation of this new relationship with additional independent sites (Pech Rouge)
306 during 2018 confirmed the ability to predict SAWC from a punctual $\delta^{13}\text{C}$ measurement. The
307 RMSE decreased to 32 mm for the year 2018, which corresponds to satisfactory prediction.
308 However, the predicted SAWC values larger than 100 mm were significantly higher than the
309 measured ones.

310

311 **4. Discussion**

312

313 *4.1 Relationship between SAWC and vineyard water status*

314 The investigated situations were chosen to represent a large variety of soil depth and soil
315 characteristics in relation to the SAWC, including soils with shallow groundwater and different
316 rooting constraints, as reported by Leenaars et al. (2018). Despite these greatly different
317 situations, satisfactory linear relationships were found between $\delta^{13}\text{C}$ and SAWC during each

318 year. These results are new. Previously, $\delta^{13}\text{C}$ as a surrogate for the vineyard water status
319 was largely used to precisely determine soil-related terroir factors (van Leeuwen et al., 2009;
320 2018). The vineyard water status depends on the FTSW present within the rooted horizons.
321 During the driest growing seasons, the vineyard soil provides storage water in relation to its
322 SAWC, considered as the maximum stored water within the soil. Our results show a
323 relationship between the $\delta^{13}\text{C}$ plant surrogate and the SAWC. The main hypothesis mainly
324 relates to the fact that vine roots infiltrate the horizons included with the SAWC calculation.

325

326 *4.2 Climatic determinant of the SAWC predictions*

327 The large variations of annual precipitation during the 4 years produced a variation of the
328 water supply during the growing season mainly via the soil water storage before bud break.
329 The 2016 precipitation was largely below the 25-year annual precipitation average, and the
330 water recharge before bud break can be considered incomplete. Conversely, the recharge
331 during the other years was higher and corresponded to at least 200 mm.

332 Except for the year 2016, the trend of the relationship between $\delta^{13}\text{C}$ and SAWC was
333 conserved despite differences in precipitation that occurred during the growing season. The
334 linear relationships present a relative stability, particularly with extreme situations. Higher
335 SAWCs correspond to sites with sufficient water recharge to preserve a low vine water stress
336 during the ripening, regardless of year. Conversely, lower SAWCs correspond to sites with
337 shallow soils or soils with a rooting limit. The water recharge is not sufficient for the years,
338 and the sites always have high $\delta^{13}\text{C}$ values. The variations between years are significant for
339 the sites with a medium SAWC and are more sensitive to precipitation during the summer
340 period. For example, site 7 (121 mm) provided a very low $\delta^{13}\text{C}$ due to a storm event at the
341 beginning of August 2017. The year 2016 corresponds to a severe water deficit due to an
342 incomplete water recharge of the SAWC. Therefore, the relationship from the 2016 dataset
343 underestimates the SAWC.

344

345 *4.3 Vine variety determinant of $\delta^{13}\text{C}$ variability*

346 $\delta^{13}\text{C}$ can be prone to variations across the different vine varieties, related to different
347 sensitivities to water stress (de Souza et al., 2005). In this case study, merging five different
348 vine varieties could constitute a disturbing effect. Indeed, the $\delta^{13}\text{C}$ values measured in two
349 sites with the same SAWC but with a different variety do not precisely express the same
350 corresponding minimal values of pre-dawn leaf water potential. The specific driest year of
351 2016 could also exacerbate the variations due to the variety (de Souza et al., 2005).

352 However, the impact of vine variety on the relation between $\delta^{13}\text{C}$ and pre-dawn leaf water
353 potential could be strongly questioned. On one hand, the calibration of the linear relationship
354 for the same grapevine variety between $\delta^{13}\text{C}$ and pre-dawn leaf water potential shows
355 relatively scattered data. For example, the linear relationship explained only 70% of the
356 variance in the case of the Tempranillo variety (Santesteban et al., 2012). Guix et al. (2007)
357 found only 80% of the explained variance for Syrah in the same Peyne valley. Additionally,
358 the relationship from four different varieties showed 95% of the explained variance
359 (Gaudillère et al., 2002). Gomez-Alonso and Garcia-Romero (2010) tested eight varieties in
360 the same site with the same soil conditions. The standard deviation of $\delta^{13}\text{C}$ measurement
361 was only 0.7. Restricting $\delta^{13}\text{C}$ to a unique vine variety is therefore not recommended since
362 the added value to the $\delta^{13}\text{C}$ -SAWC relationship is far from being demonstrated, whereas it
363 may induce sampling difficulties related to the exclusive locations of each vine variety in
364 specific pedo-climatic situations.

365

366

367 *4.4 Added value of a multivariate approach*

368 The climatic variability and intrinsic $\delta^{13}\text{C}$ variations were combined with a relationship
369 between a mean of each annual measurement of $\delta^{13}\text{C}$ and SAWC. The results outperformed
370 the relationships for each study year, excluding 2016. The relationships did not change for
371 the sites with extreme SAWC, high or low. Conversely, the $\delta^{13}\text{C}$ mean for the site with
372 medium SAWC moderated the interannual variability. This integrated relationship was

373 successfully tested for the independent Pech Rouge sites. The first analysis of figure 4 (right)
374 seems to show an overestimation of SAWC > 100 mm. The measurement of SAWC in the
375 case of thin soils with high coarse fragment content and with cracked bedrock is
376 questionable. The contribution of coarse fragments to the water storage was included in the
377 SAWC. However, the measurements of specific water content in coarse fragments were
378 disturbed by the time of water extraction and pore connectivity. The lateral variability of
379 cracks is not visible with punctual pit observations, especially in thin soils over limestones. In
380 this specific case, $\delta^{13}\text{C}$ probably constitutes a better integrated parameter to estimate the
381 real SAWC than the conventional SAWC measurement.

382

383 4.5 Limitations and further approaches

384 The study of four contrasted consecutive years shows that the use of the $\delta^{13}\text{C}$ as a surrogate
385 of SAWC is mainly dependent on the water recharge before bud break especially for the low
386 SAWC. Furthermore, this surrogate cannot be applied in irrigated crops, which disconnect
387 the SAWC and the water status of the plant. The importance of the climate-dependent water
388 status argues for consolidating the relationships with additional study years with atypical
389 water recharge, which was not monitored in this work. For example, a large amount of rain
390 during the summer would dramatically decrease the $\delta^{13}\text{C}$.

391 The distribution of SAWC for the Payne sites had an effect on the relationships between
392 $\delta^{13}\text{C}$ and SAWC. Only two sites presented a SAWC higher than 250 mm, and the majority of
393 the Payne sites had medium SAWC values between 100 and 200 mm. The relationship was
394 more sensitive to extreme SAWC and future sites with lower SAWC and higher SAWC in the
395 Payne catchment might ameliorate the genericity of the relationship. In the same way, the
396 validation in Pech Rouge suffered a lack of sites with high SAWC.

397 The relation between $\delta^{13}\text{C}$ and SAWC was established in restricted crop situations, namely,
398 rainfed vineyards. $\delta^{13}\text{C}$ variations on other plants than vineyards have been demonstrated to
399 be reliable to water stress. The present study could be extended to other land uses, with care

400 in characterising the maximum rooting depth, which could induce underestimation of the
401 SAWC, particularly in the case of annual plants.

402 Beyond the above-evoked limitation, this work demonstrated that $\delta^{13}\text{C}$ can be considered in
403 some particular landscapes as a simple and inexpensive surrogate for determining SAWC. It
404 could therefore be used in further digital soil mapping (DSM) approaches that deal with
405 SAWC as new soil input for calibrating or validating the DSM models. In addition to
406 considerably increasing the density of measurement, the use of $\delta^{13}\text{C}$ would lead to better
407 accounting of the contribution of deep horizons in the case of perennial plants.

408

409 **5. Conclusions**

410

411 This work demonstrated that the $\delta^{13}\text{C}$ values of grapes can be considered as a simple and
412 inexpensive surrogate for determining SAWC in rainfed vineyards. Moreover, the use of
413 proxies based on the perennial plant response, such as $\delta^{13}\text{C}$, provides first order information
414 for comparison with theoretical SAWC, especially for the analysis of the contribution of deep
415 horizons. Successive monitored years, with the means of each annual $\delta^{13}\text{C}$, combined
416 climatic variability and intrinsic $\delta^{13}\text{C}$ variations. The relations did not change for the sites with
417 extreme SAWC, high or low. Conversely, the $\delta^{13}\text{C}$ means for the sites with medium SAWC
418 moderated the interannual variability. This integrated relationship between the $\delta^{13}\text{C}$ means
419 and SAWC was successfully tested for 8 independent sites. However, specific years without
420 sufficient soil water recharge are not appropriate for the use of a SAWC surrogate. Finally,
421 extensions of this study to other agro-systems are required to better define the potential area
422 of use of $\delta^{13}\text{C}$.

423

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430

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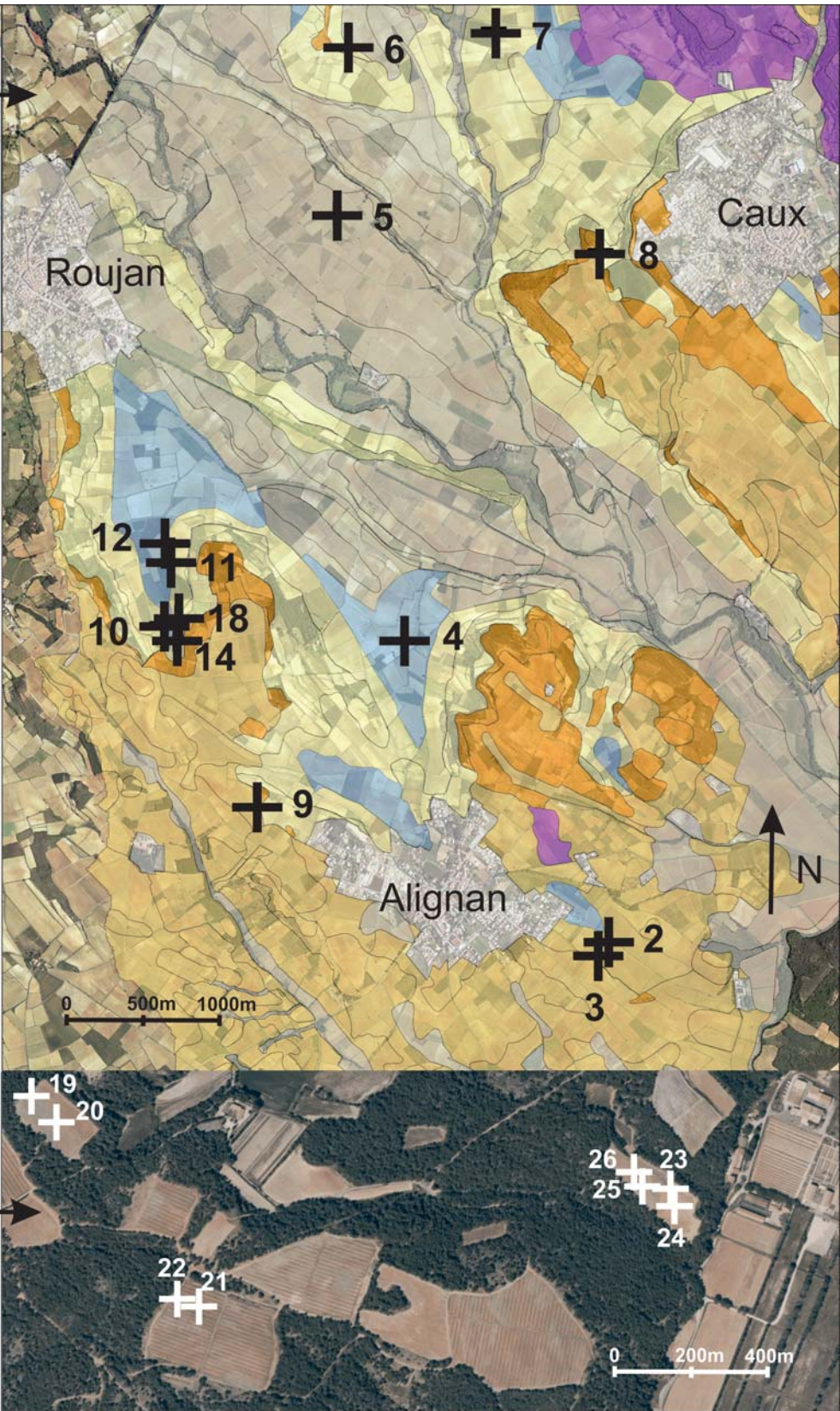
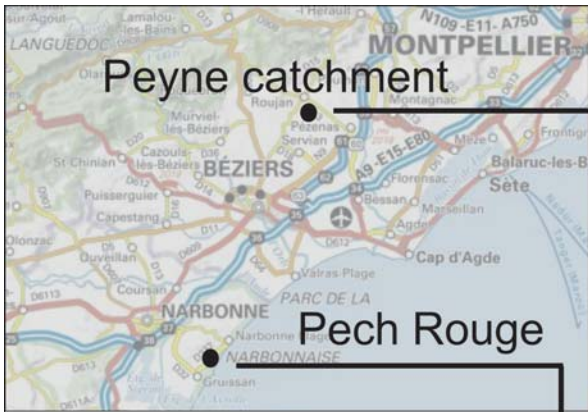
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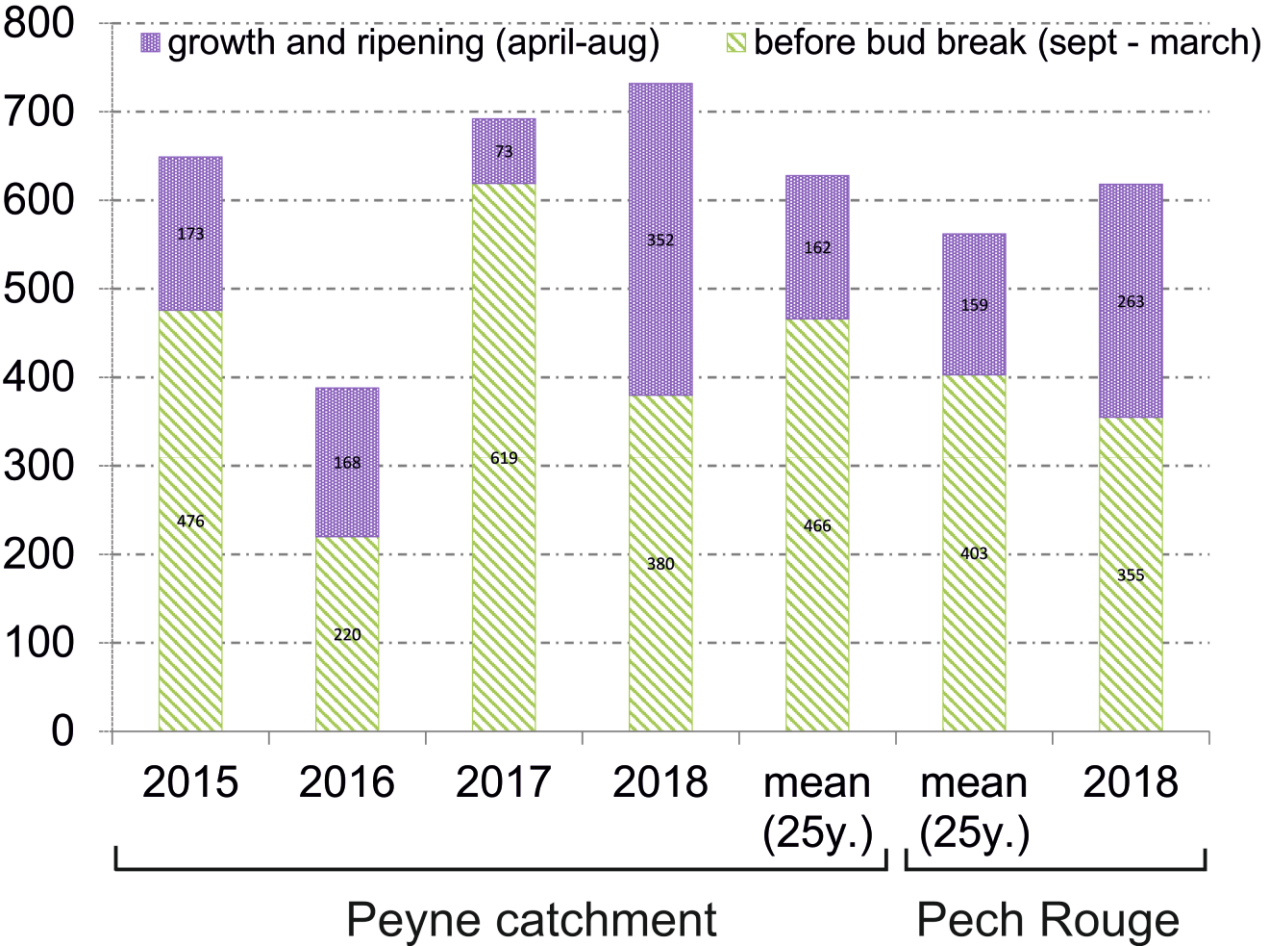
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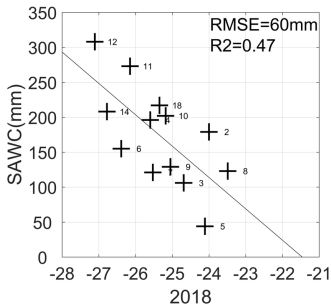
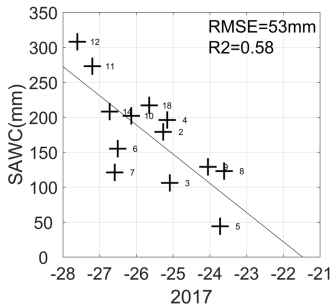
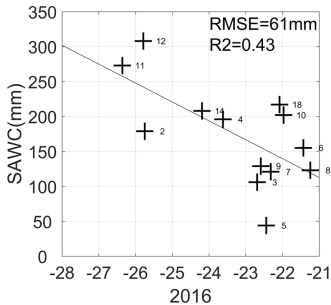
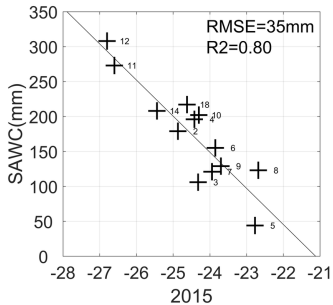
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-  soils over alluvial deposits
-  shallow soils over loose sandstone
-  deep soils over loose sandstone
-  shallow soils over limestone
-  soils over old alluvial deposits
-  soils over volcanic materials
-  measurement site







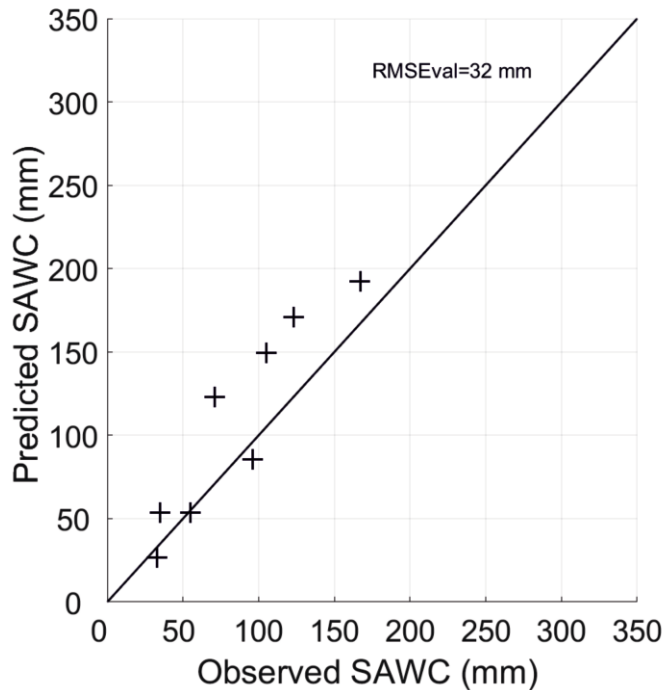
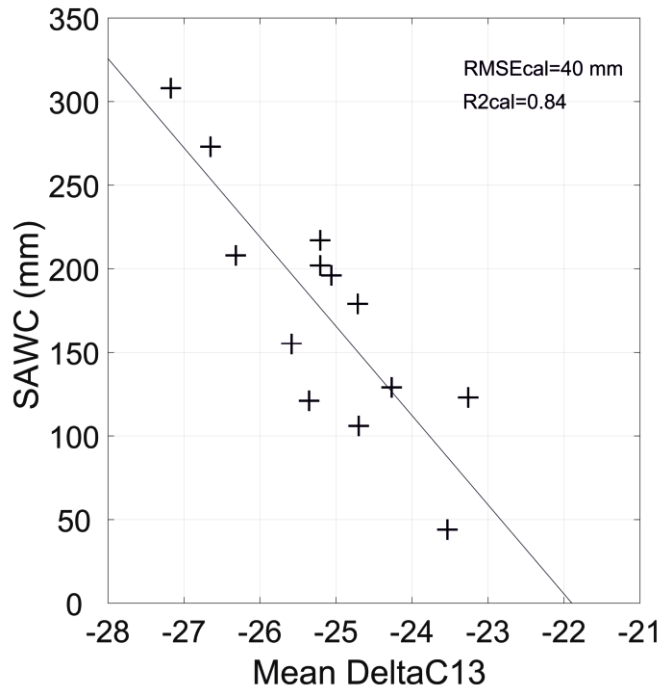


Table1: The Payne and Pech Rouge datasets

Site	WRB Class	Geological setting	Shallow Groundwater	soil depth (m)	actual SAWC (mm)
Payne					
2	Calcisol (vertic)	Old clayey alluvial deposits	yes	2.70	179
3	Calcisol	Old clayey alluvial deposits	no	1.35	105
4	Gleyic Cambisol	Loose sandstone in bottom area	yes	3.50	197
5	Skeletal Cambisol (gleyic)	Alluvial stony deposits	yes	2.50	44
6	Calcisol	Loose sandstone on hillslope	No	1.10	155
7	Calcisol (leptic)	Loose sandstone on hillslope	No	1.00	121
8	Calcisol (leptic)	Lacustrine limestone on the top of the hill	No	0.65	123
9	Skeletal Calcisol	Lacustrine limestone on the top of the hill	No	1.70	129
10	Calcisol	Loose sandstone on hillslope	No	1.55	202
11	Cambisol	Loose sandstone in bottom area	Yes	2.20	274
12	Cambisol	Loose sandstone in bottom area	Yes	2.50	308
14	Calcisol (gleyic)	Loose sandstone on hillslope	No	2.00	208
18	Calcisol	Loose sandstone on hillslope	No	1.65	217
The whole Payne dataset : mean (std)				1.90(0.79)	174 (72)
Pech Rouge					
19	Skeletal Leptosol	Micritic limestone	No	0.40	33
20	Skeletal Calcisol	Micritic limestone	No	1.50	96
21	Calcisol (clayic)	Micritic limestone	No	1.40	123
22	Skeletal Leptosol	Orbitolina limestone	No	0.50	35
23	Calcisol	Colluvial deposits	No	2.00	167
24	Calcisol	Colluvial deposits	No	0.95	105
25	Skeletal Calcisol	Micritic limestone	No	0.70	55
26	Skeletal Calcisol	Micritic limestone	No	0.90	71
The whole Pech Rouge dataset : mean (std)				1.04 (0.56)	86 (46)

Table 2 : The whole $\Delta C13$ results during the 4 years

$\Delta C13$	Peyne Catchment				Pech Rouge
year	2015	2016	2017	2018	2018
Mean	-24.49a	-23.27b	-25.64c	-25.34ac	-23.89ab
Std	1.24	1.73	1.30	1.09	1.26
RStd	5	7	5	4	5
Min	-26.80	-26.36	-27.61	-27.11	-25.50
Max	-22.68	-21.24	-23.61	-23.49	-22.2
N	13	13	13	13	8

Differents letters denote statistically significant differences between means (ANOVA and Tukey's HSD based on the Student distribution, at $P < 0.01$)