Carbon isotope discrimination as a surrogate for soil available water capacity in rainfed areas: A study in the Languedoc vineyard plain

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Highlights

Four contrasting years were monitored to investigate different soil water conditions.

The Soil Available Water Capacity (SAWC) was measured on 21 sites.

The integrated relationship between the mean of $\delta^{13}C$ and SAWC was successfully tested.

$\delta^{13}C$ of grapes can be considered as a simple and inexpensive surrogate for determining SAWC.

Abstract

Soil available water capacity (SAWC) is a key soil function for plant growth. Classical SAWC characterization requires time consuming determinations of bulk density and specific soil moisture contents. Consequently, these data are extremely sparse in existing soil databases. Using surrogates of the vegetal response to characterize SAWC across a great number of sites constitutes a promising perspective. The carbon isotope ratio ($\delta^{13}C$) measured in a plant organ is largely known as an indicator of plant water status. The aim of the paper is to test $\delta^{13}C$ as an indicator of SAWC in rainfed vineyard.

$\delta^{13}C$ values of grapes at harvest time were measured at 21 sites on the Languedoc vineyard plain with contrasting SAWC (33 to 308 mm) for four years (2015 to 2018) with contrasting annual precipitation (from 390 to 715 mm). The relationships between $\delta^{13}C$ and SAWC determined using a classical approach (soil description, soil sampling and laboratory methods) were satisfactory for all years (RMSEs from cross validation were between 35 and 61 mm). Better relationships were obtained between $\delta^{13}C$ and SAWC for years that showed a full winter recharge of SAWC (2015, 2017 and 2018). Averaging the $\delta^{13}C$ measurements over such years provided an even better relationship (R^2=0.85; RMSE 32 mm), which was successfully validated in distant sites on the Languedoc vineyard plain.

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

1. Introduction

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

Determining the SAWC requires costly and time-consuming measurements of soil properties. Bulk density and volumetric water content at wilting point and field capacity require undisturbed sampling and physical measurements in the laboratory (Klute, 1986; Bruand and Tessier, 2000). Moreover, determination of the SAWC for perennial plants having a deep root system requires investigation of the deep horizons, which are not always accessible. Consequently, the SAWC data are extremely sparse in existing soil databases, which prevents the use of these databases as inputs for Digital Soil Mapping approaches (McBratney et al., 2003) as is currently done for other more current soil properties (e.g., Organic Carbon, textural fractions). To overcome this problem, pedotransfer functions (Rawls et al., 1982; Al Majou et al., 2008) can be used to estimate the specific water content from available soil properties, which has allowed the production of SAWC maps (Leenaars et al., 2018, Dobarco et al., 2019). However, these functions convey a great amount of uncertainty that could generate significant errors in SAWC maps (Dobarco et al., 2019). Therefore, the increase in well-characterized sites with regard to SAWC is a prerequisite for a significant improvement of SAWC maps.

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

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

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

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

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

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

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

2. Materials and methods

2.1 Study areas

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

The soil pattern of the Peyne catchment arises mainly from variations in lithology, and the main soil characteristics depend on the type of parent material (figure 1). The entire valley is underlain by heterogeneous Miocene marine calcareous sandstone and lacustrine limestone, which form the parent material of several types of soil, including calcaric leptosols, calcaric regosols, and calcisols (IUSS working group WRB, 2015). These Miocene sediments are partly overlain by successive alluvial deposits ranging from Pliocene to Holocene, and they differ in their initial nature and in the duration of weathering conditions. Therefore, these sediments have produced intricate soil patterns that include a great range of soil types such as calcisols, endogleyic calcisols, luvisols (chromic), and fluvisols. Recent volcanic activity and local transport of colluvium material along slopes have added to the complexity of the soil pattern. Consequently, the soils of the valley present contrasting characteristics in terms of texture, stoniness and soil depth, which determine their SAWC.

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

<Figure 1 here>

2.2 Site sampling

The sites were chosen to be representative of the diversity of soil characteristics, especially soil depth and SAWC (table 1 and figure 1). A total of 13 sites were located in the Peyne catchment to calibrate the relations, and 8 additional sites were located in the Pech Rouge INRA station to validate the relations with independent sites. A site corresponds to approximately 15 m² (9 vines) within the vineyards to limit the spatial variability of soil properties and assign a SAWC to a site with a maximum of precision. Regarding agronomical aspects, the vineyards were chosen (i) to be representative of the regional vineyards and (ii) to avoid the situations where the relation between the SAWC and the vine water status may be disturbed (e.g., irrigated zones; young vineyards with insufficient root systems). The vineyards were 15-20 years old and without irrigation. The plantation density (4000 plants/ha), the trellising (2 stages), the pruning system (double cordon) and the number of buds (16 to 20) were the same at all sites. However, the variety differed, with Syrah (sites 6,9), Cabernet Sauvignon (sites 4,10,18), Sauvignon blanc (site 14), Grenache noir (site 5,8), and Merlot (sites 2,3,7,11,12).

2.3Soil survey

Soil pits were dug near each selected site during the winter of 2016 and the soil morphological parameters were observed in the field (soil depth, structure, colour, stones, roots abundance) according to the guidelines for soil description (FAO, 2006). The soil horizons were determined in relation to these descriptions, and bulk densities (ρ_b) were measured by core sampling with 100 cm^3 stainless-steel cylinders (Blake and Hartge, 1986) with 6 replicates per horizon. ρ_b was determined as the ratio between the dry soil mass and the total core sampling volume. Moreover, each sample was sieved to extract the coarse fragments (e.g. >2mm), and the bulk density of the fine earth (ρ_{bFE}) was determined as the ratio between the dry soil mass without the coarse fragments and the total core sampling volume without the volume corresponding to the coarse fragments. This volume was calculated from the mean bulk density of the coarse fragments (ρ_{bCF}) according to the type of pebbles already measured in the Peyne catchment and in Pech Rouge station (e.g. old alluvial pebbles 2.8 and limestone 2.5). Undisturbed soil samples of over 500 g were taken in each horizon for characterisation of the specific water retention at -33 kPa (field capacity) and -1500 kPa (wilting point) according to the pressure chamber method (Klute, 1986). Disturbed soil samples localized in the same horizons were used for classical texture and coarse-fragment analysis. The samples were sieved to separate pebbles greater than 2 mm in diameter from the fine earth. The particle size distribution was analysed following the destruction of organic matter and dispersion with sodium hexametaphosphate (AFNOR, N FX 31-107). The clay (< 2 µm) and silt (2-50 µm) contents were quantified by sedimentation, and sand (50-2,000 µm) was measured via sieving. The detailed results of the soil survey are summarized in Table 1.

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 (Tetegan 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.

$$SAWC = \sum_{horizon=1}^{n} (Z_{(horizon)} \times (Ws - Wr) \times \rho\mathrm{bFE} \times \left\{10 - \frac{CF \times \rho\mathrm{b}}{10 \times \rho_{bCF}}\right\})$$

Where :

SAWC (mm)	total soil available water capacity
n	number of actual horizon
$Z_{(horizon)}$ (m)	thickness of the horizon
Ws *	mass water content at 0.33 bar
Wr*	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>

2.5 δ^{13}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 Peyne 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). δ^{13}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 δ^{13}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 δ^{13}C lower than -26‰; conversely, the water deficit is severe with a δ^{13}C higher than -24‰.

2.6Experimental protocol

The Peyne sites were first chosen to calibrate the relationship between δ^{13}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 Peyne sites for each year.

Three years (2015, 2017 and 2018) were chosen to calculate the δ^{13}C mean for each site within the Peyne catchment and calibrate a new multidate relationship between δ^{13}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).

3. Results

3.1 Precipitation

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

<Figure 2 here>

3.2 $\delta^{13}C$

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

<Table 2 here>

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

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

<Figure 3 here>

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

<Figure 4 here>

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

4. Discussion

4.1Relationship between SAWC and vineyard water status

The investigated situations were chosen to represent a large variety of soil depth and soil characteristics in relation to the SAWC, including soils with shallow groundwater and different rooting constraints, as reported by Leenaars et al. (2018). Despite these greatly different situations, satisfactory linear relationships were found between $\delta^{13}C$ and SAWC during each year. These results are new. Previously, $\delta^{13}C$ as a surrogate for the vineyard water status was largely used to precisely determine soil-related terroir factors (van Leeuwen et al., 2009; 2018). The vineyard water status depends on the FTSW present within the rooted horizons. During the driest growing seasons, the vineyard soil provides storage water in relation to its SAWC, considered as the maximum stored water within the soil. Our results show a relationship between the $\delta^{13}C$ plant surrogate and the SAWC. The main hypothesis mainly relates to the fact that vine roots infiltrate the horizons included with the SAWC calculation.

4.2Climatic determinant of the SAWC predictions

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

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

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

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

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

4.4 Added value of a multidate approach

The climatic variability and intrinsic $\delta^{13}C$ variations were combined with a relationship between a mean of each annual measurement of $\delta^{13}C$ and SAWC. The results outperformed the relationships for each study year, excluding 2016. The relationships did not change for the sites with extreme SAWC, high or low. Conversely, the $\delta^{13}C$ mean for the site with medium SAWC moderated the interannual variability. This integrated relationship was successfully tested for the independent Pech Rouge sites. The first analysis of figure 4 (right) seems to show an overestimation of SAWC > 100 mm. The measurement of SAWC in the case of thin soils with high coarse fragment content and with cracked bedrock is questionable. The contribution of coarse fragments to the water storage was included in the SAWC. However, the measurements of specific water content in coarse fragments were disturbed by the time of water extraction and pore connectivity. The lateral variability of cracks is not visible with punctual pit observations, especially in thin soils over limestones. In this specific case, $\delta^{13}C$ probably constitutes a better integrated parameter to estimate the real SAWC than the conventional SAWC measurement.

4.5Limitations and further approaches

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

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

The relation between $\delta^{13}C$ and SAWC was established in restricted crop situations, namely, rainfed vineyards. $\delta^{13}C$ variations on other plants than vineyards have been demonstrated to be reliable to water stress. The present study could be extended to other land uses, with care in characterising the maximum rooting depth, which could induce underestimation of the SAWC, particularly in the case of annual plants.

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

5. Conclusions

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

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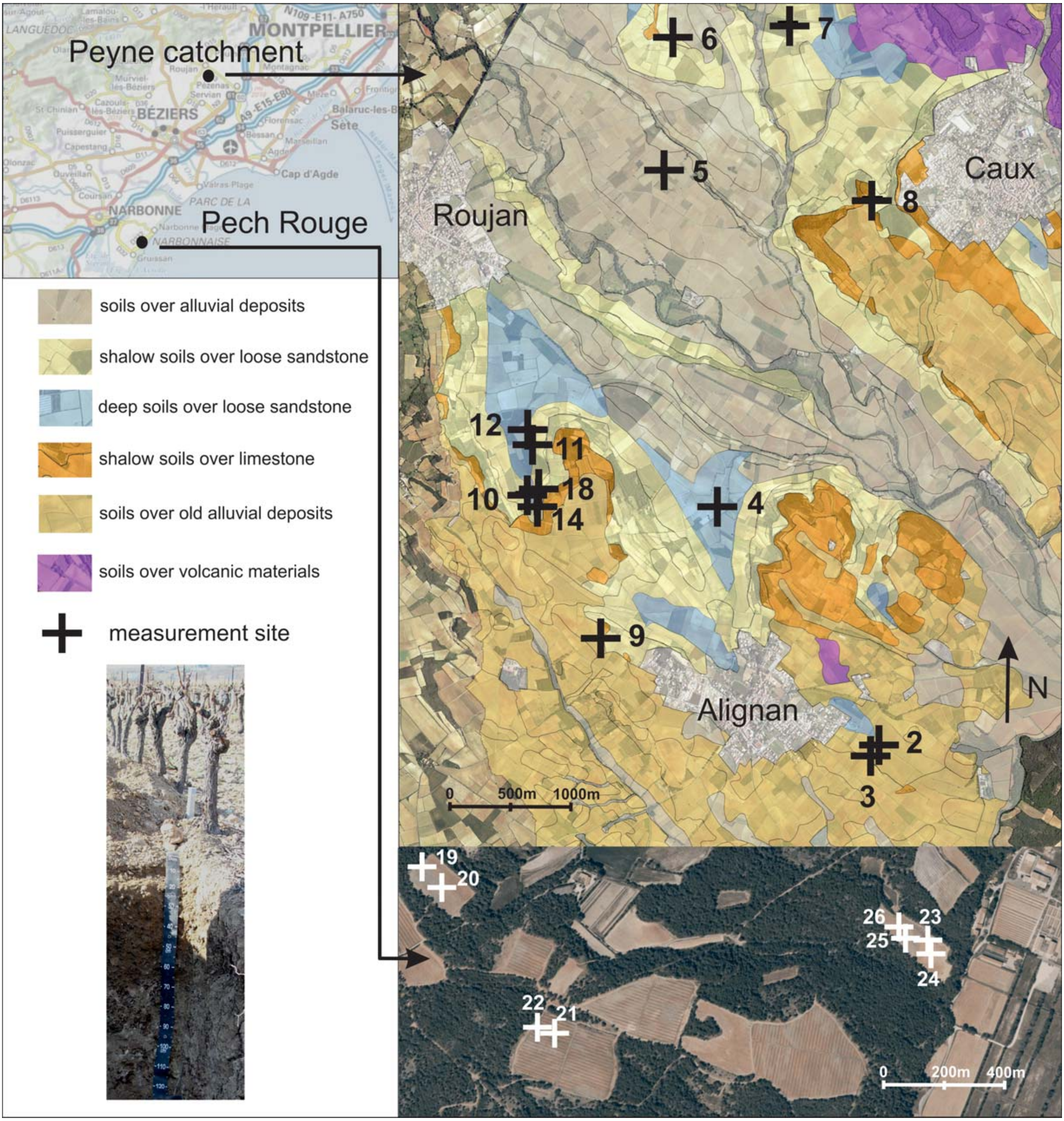

Peyne catchment
Pech Rouge
MONTPELLIER
BÉZIERS
NARBONNE
Sète
Cap d'Agde
Roujan
Caux
Alignan
soils over alluvial deposits
shalow soils over loose sandstone
deep soils over loose sandstone
shalow soils over limestone
soils over old alluvial deposits
soils over volcanic materials
measurement site
N
0
500m
1000m
200m
400m
2
3
4
5
6
7
8
9
10
11
12
14
18
19
20
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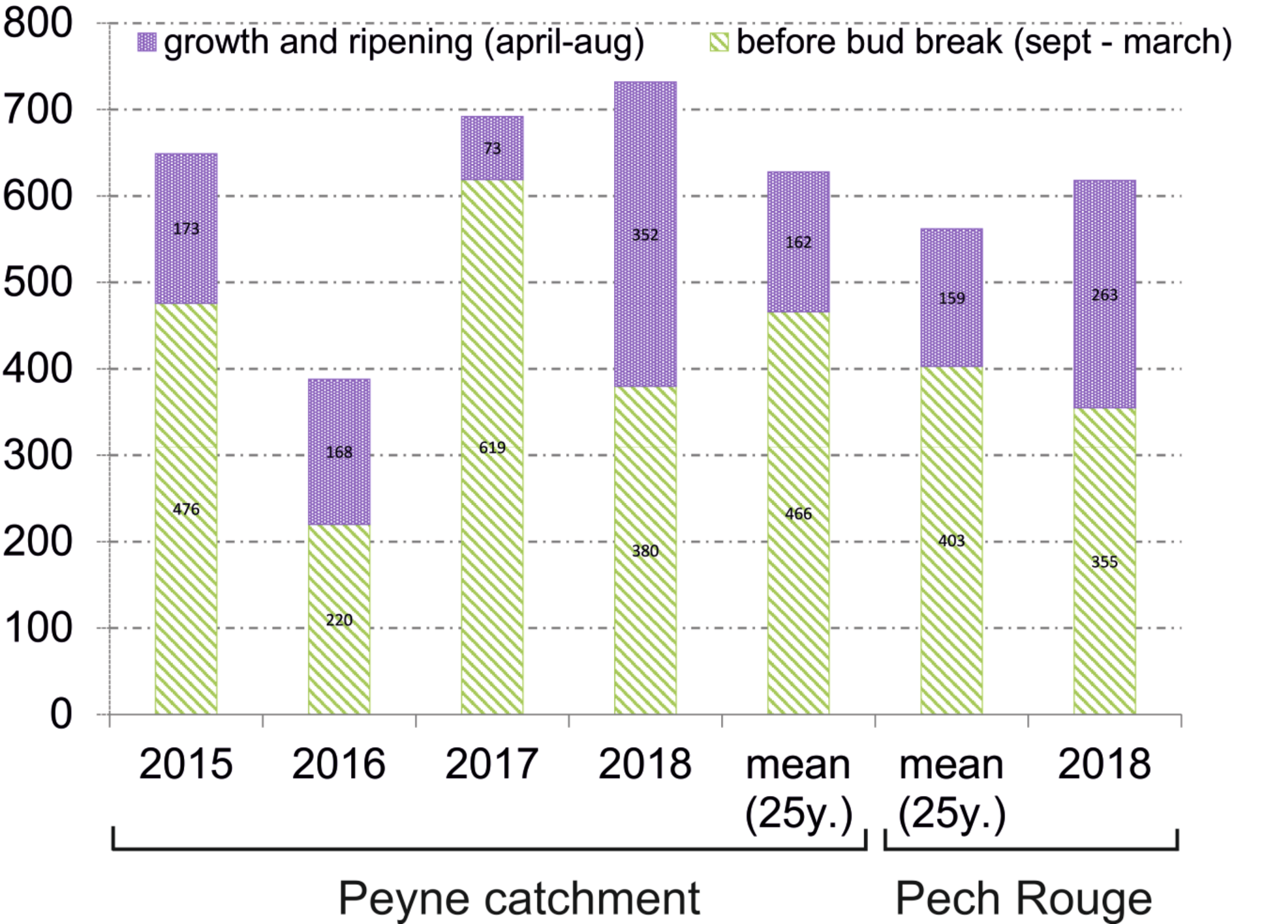
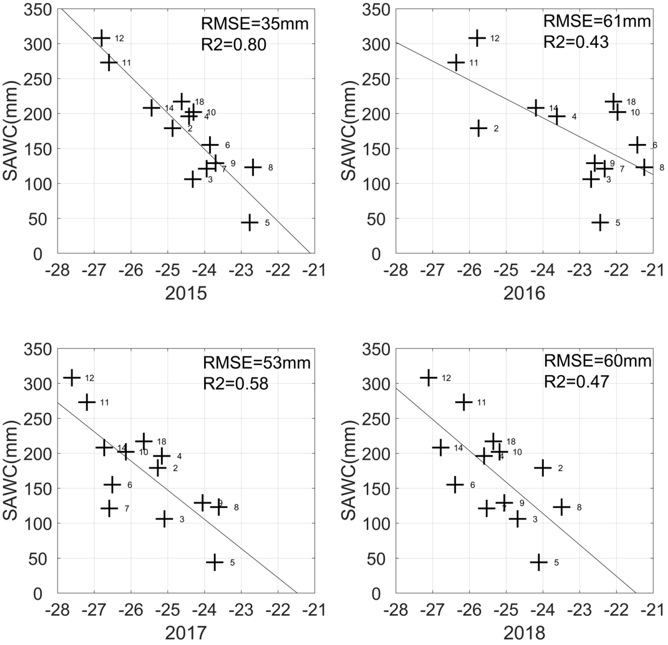
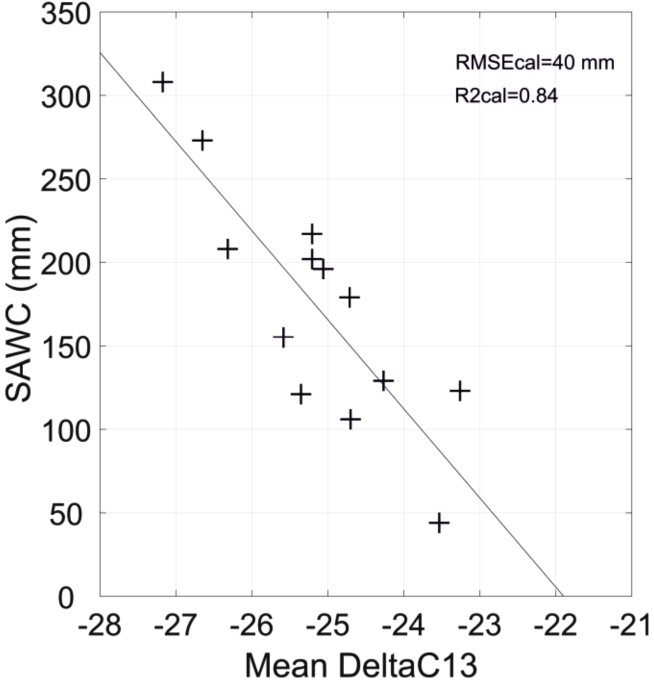
22
23
24
25
26

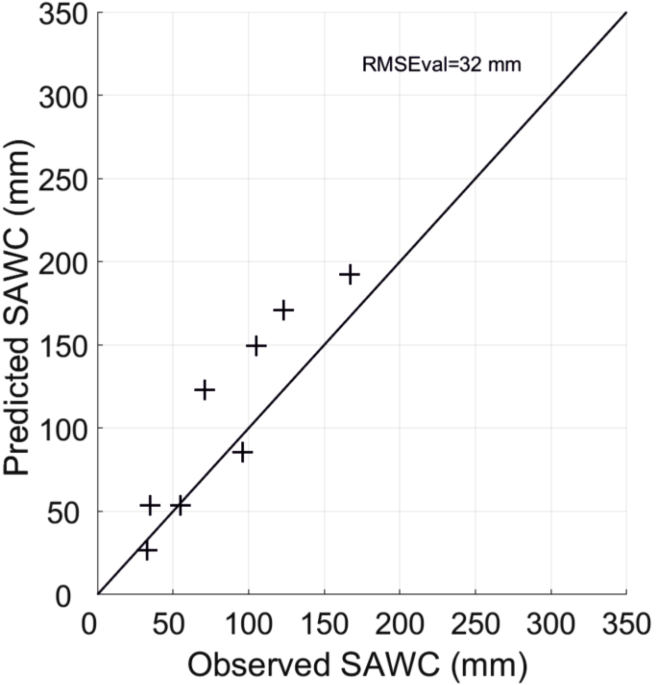


800
700
600
500
400
300
200
100
0
growth and ripening (april-aug)
before bud break (sept - march)
173
476
168
220
73
619
352
380
162
466
159
403
263
355
2015
2016
2017
2018
mean (25y.)
mean (25y.)
2018
Peyne catchment
Pech Rouge


RMSE=35mm
R2=0.80
SAWC(mm)
2015
RMSE=61mm
R2=0.43
SAWC(mm)
2016
RMSE=53mm
R2=0.58
SAWC(mm)
2017
RMSE=60mm
R2=0.47
SAWC(mm)
2018



RMSEcal=40 mm
R2cal=0.84
SAWC (mm)
Mean DeltaC13
350
300
250
200
150
100
50
0
-28
-27
-26
-25
-24
-23
-22
-21



RMSEval=32 mm
Predicted SAWC (mm)
Observed SAWC (mm)
350
300
250
200
150
100
50
0
0
50
100
150
200
250
300
350

Table1: The Peyne and Pech Rouge datasets

Site	WRB Class	Geological setting	Shallow Groundwater	soil depth (m)	actual SAWC (mm)
Peyne					
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	**Skeletic 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	**Skeletic 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 Peyne dataset : mean (std)		1.90(0.79)	**174 (72)**
Pech Rouge					
19	**Skeletic Leptosol**	**Micritic limestone**	No	0.40	**33**
20	**Skeletic Calcisol**	**Micritic limestone**	No	1.50	**96**
21	**Calcisol (clayic)**	**Micritic limestone**	No	1.40	**123**
22	**Skeletic Leptosol**	**Orbitolina limestone**	No	0.50	**35**
23	**Calcisol**	**Colluvial deposits**	No	2.00	**167**
24	**Calcicol**	**Colluvial deposits**	No	0.95	**105**
25	**Skeletic Calcisol**	**Micritic limestone**	No	0.70	**55**
26	**Skeletic Calcisol**	**Micritic limestone**	No	0.90	**71**
		The whole Pech Rouge dataset : mean (std)		1.04 (0.56)	**86 (46)**

Table 2 : The whole ∆C13 results during the 4 years

∆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 $P<0.01$)