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Dr. Antonio Paz González

Editor Special Issue "Multifractal Analysis in Soil Systems"

Nonlinear Processes in Geophysics

Subject: Submission of revised manuscript to *Nonlinear Processes in Geophysics*

Dear Editor,

On behalf of all authors, I would like to submit the following manuscript entitled: "Multifractal behaviour of the soil water content of a vineyard in NW Spain during two growing seasons", by José Manuel **Mirás-Avalos**, Emiliano **Trigo-Córdoba**, Rosane **da Silva-Dias**, Irene **Varela-Vila**, and Aitor **García-Tomillo**.

We thank all the comments and suggestions posed by the reviewers. All comments were taken into account and changes according to them were performed throughout the text. A specific answer to all the reviewers' comments is provided at the end of this letter. Besides, we moved a table and two figures to supplementary materials in order to alleviate manuscript length. We also corrected several mistakes in the reference list.

We hope that, at its present form, our manuscript would reach the high quality standards for publication on *Nonlinear Processes in Geophysics*.

Looking forward to hearing from you.

Sincerely yours,

José Manuel Mirás Avalos
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Reviewer: 1 (M.G. Wilson)

This paper is precise and concrete. The paper describes dynamics of soil water content and considers the multifractality of these time data series of a vineyard in NW Spain. The paper is showing scaling properties of soil water content time series, these properties were different for the rain-fed and irrigation use, and higher heterogeneity under irrigation conditions

Thank you very much for your comment, Dr. Wilson.

Reviewer: 2

The aim of this paper is to describe soil water dynamics in vineyard and to assess multifractality. This topic is very interesting, because there is no application of multifractality to the temporal evolution of the soil water content in vineyard under two different water supply methods. This paper presents on an interesting subject and well written. The multifractality is analysed using the classical method of moments A question will be if the authors have detected the effects of seasonal trend on the multifractal analysis

Thank you very much for your comments. Regarding your question about the effects of seasonal trend on the multifractal analysis, we are not sure about what you mean. If you refer to differences in multifractal parameters from one season to the other; we addressed this on the former version by stating that “2012 data series presented a higher hetereogeneity than those from 2011” (page 8, lines 13-14). In the current version of the manuscript we added “Moreover, the width of the Dq spectra increased from 2011 to 2012 in both treatments, mainly in the 20 and 40 cm depths” (page 8, lines 27-28). We also added “Our results showed that the width of the singularity spectra increased in both treatments from 2011 to 2012 (Table 2)” (page 9, lines 26-27). Finally, in the conclusions section, we added “, which tended to increase in the second year of the study (2012)” (page 10, lines 21-22). We hope that these additions answer your question.

Specific and technical comments

Page 3 line 18 when calculating the soil water budget would have to take into account both the interception, and surface storage, and consider surface runoff

Yes, you are right, but we did not consider surface runoff because it was negligible on the studied plot. Surface storage and water interception by the canopy were not accounted for because our objective was not calculate a precise soil water budget but provide irrigation according to midday stem water potential readings and crop evapotranspiration, as described in this portion of the manuscript.

Page Line 16 “0.4 mg of suspended soils”, units must be mg/l or other concentration units.

Yes, you are right, it is mg/L. We corrected it in the revised version of the manuscript.

Page 4 line 8 "..the equation provided by the manufactured was used for transforming permittivity data registered by the probes into soil water content" justify this statement, because FDR calibration strongly depends on soil type.

Yes, you are right, soil type greatly influences the FDR probe readings. However, we used the equation provided by the manufacturer because we did not use these measurements for scheduling irrigation since we relied on stem water potential readings. Besides, the default equation can be used for relative or differential measurements since we are comparing the performance of two probes in the same soil but under two different irrigation regimes. We included a brief text explaining this and providing a citation from a work by Paraskovas et al. (2012) in International Agrophysics in order to justify our procedure.

Page 7 line 15, add "and soil evaporation"

Added as suggested.

Page 7. Line17 ". . .Indeed, our results suggest that the water amount applied through irrigation was enough for fulfilling vineyard water requirements over the two growing seasons studied" justify this statement Table 1 Use ETc data, I don't know if the depth of irrigation dose is net or gross. The dose of irrigation calculated seems very low, because if we calculate the approximate dose irrigation as precipitation less than 50% of crop evapotranspiration assuming negligible value interception, surface storage and surface runoff, the value obtained would be much higher than the value shown in table

We removed the sentence because we did not provide data on grapevine vegetative growth, yield and berry quality, which were slightly affected by irrigation and made us to conclude that. These data are pending for publication and have been submitted to another journal; therefore, we considered removing this sentence as the best option since it does not affect the main focus and conclusions from the current manuscript.

We agree with you in the sense that Table 1 led to confusion since the data reported there referred to the whole period of measurements and not exclusively to the irrigation period. Besides, this table provided similar information to that displayed in figure 2. Therefore, we removed the table from the main manuscript and moved it to supplementary materials and added the information referred to the irrigation period for each year.

Fig 3 year 2011 around day 230 there is increase in rain-fed treatment in 20 cm depth but this increase is not showed in irrigated plot.

This is true; it was caused by three rainfall events happening on consecutive days from the day 234 to the day 236, accumulating 15 mm. The 20 cm depth sensor in the rain-fed treatment responded quickly to this increase (increases in soil water content were observed in day 235), whereas the *sensor in the irrigated treatment responded more slowly (day 237). Moreover, when checking the data, we observed that this increase in the soil water content at 20 cm depth in the rain-fed treatment lift the values up to those observed in the irrigated treatment at the same depth. Therefore, it seemed to be just a delay in the response of the sensor since the water content at 20 cm depth in the irrigated treatment also increased (in a lower proportion than that in the rain-fed treatment) after two days of the last rainfall event.*

Fig 5 and 7. Improve figure quality

Thank you, quality of the figures has been improved as you suggest. However, in order to reduce manuscript length, we moved figure 5 to the supplementary material.

Multifractal behaviour of the soil water content of a vineyard in NW Spain during two growing seasons

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Abstract

Soil processes are characterized by a great degree of heterogeneity, which may be assessed by scaling properties. The aims of the current study were to describe the dynamics of soil water content at three depths in a vineyard under rain-fed and irrigation conditions and to assess the multifractality of these time data series. Frequency domain reflectometry (FDR) sensors were used for automatically monitoring soil water content in a vineyard located in Leiro (Ourense, NW Spain). Data were registered at 30-minute intervals at three depths (20, 40 and 60 cm) between 14th June and 26th August 2011 and 2012. Two treatments were considered: rain-fed and irrigation to 50% crop evapotranspiration. Soil water content data series obeyed power laws and tended to behave as multifractals. Values for entropy (D_1) and correlation (D_2) dimensions were lower in the series from the irrigation treatment. The Hölder exponent of order zero (α_0) was similar between treatments; however, the widths of the singularity spectra, $f(\alpha)$, were greater under irrigation conditions. Multifractality indices slightly decreased with depth. These results suggest that singularity and Rényi spectra were useful for characterizing the time variability of soil water content, distinguishing patterns among series registered under rain-fed and irrigation treatments.

1 Introduction

Soil water storage variability is strongly related with topographical, geological, edaphic and vegetation factors (Braud et al., 1995). These environmental factors and processes (rainfall, evapotranspiration, runoff) do not operate independently but as a conjunction of processes with nested and complex effects. Overall, this results in a distribution of soil water storage that varies as a function of the temporal and spatial scales. Therefore, similar to other soil properties and processes (Western and Blöschl, 1999; Zeleke and Si, 2006), soil water storage along time is a complex process characterized by a lack of homogeneity; heterogeneity in space and/or time is a feature that can be described by scaling procedures.

Fractals have been widely employed in soil science, as soil properties may be described through scale invariance concepts (Tyler and Wheatcraft, 1990; Perfect et al., 1996; Vidal Vázquez et al., 2007; Biswas et al., 2012a). More recently, several authors performed multifractal studies of heterogeneous time data series. For instance, Jiménez-Hornero et al. (2010) described ozone time series using the multifractal formalism. Rodríguez-Gómez et al. (2013) used a multifractal approach for characterizing solar radiation time series.

Soil water content can be automatically estimated by using sensors that measure variations in the soil dielectric constant, since it is strongly related with soil water content (Mestas-Valero et al., 2012). This parameter is characterized by its spiky dynamics, with sudden and intense peaks of high frequency activity, mostly at soil surface. Several studies have described scaling patterns for the behaviour of sol water content spatial distribution (e.g. Kim and Barros, 2002; Biswas et al., 2012b); however, multifractal analyses of continuously measured soil water content are scarce, except for a study on rain-fed grassland (Mestas-Valero et al., 2011). Therefore, the aim of the current work was to describe soil water dynamics in a vineyard subjected to two different treatments (rain-fed and irrigated) and to assess multifractality of these data series over two consecutive seasons.

2 Materials and Methods

2.1 Description of the study area

The experiment was conducted over two consecutive growing seasons (2011-2012) in a 0.2-ha vineyard (*Vitis vinifera* L.) planted with cultivar 'Albariño', located in the experimental farm of the Estación de Viticultura e Enoloxía de Galicia (EVEGA), in Leiro (42º 21.6' N, 8º 7.02' W, elevation 115 m), Ourense, Spain (Fig. 1). Vines were grafted in 1998 on 196-17C rootstock and trained to a vertical trellis on a single cordon system (10-12 buds per vine). Rows were east-west oriented, spacings between vines and between rows were 1.25 and 2.4 m, respectively (3333 vines ha^{-1}). The soil at the site was sandy-textured (64% sand, 16% silt, 20% clay), slightly acidic (pH 6.3), medium fertility (2.7% organic matter) and with a rather shallow profile (≈1.2 m). The climate of the studied site is temperate, humid with cool nights (Fraga et al., 2014).

2.2 Experimental design

The reference evapotranspiration (ET_0) per week for the site was calculated from weather variables recorded at a station located 150 m away from the experimental vineyard using the Penman-Monteith equation (Allen et al., 1998). The ET_0 was then used, along with a constant crop coefficient (K_c = 0.8) to compute the amount of water required by the vines (Trigo-Córdoba et al., 2015). Precipitation was substracted from ET_c each week. The calculated amount of water was applied the following week.

Treatments consisted of a rain-fed control and an irrigation to the 50% of ET_c. Irrigation was applied from late June – early July (after bloom) till mid-August, approximately two weeks prior to harvest through two pressure-compensated emitters of 4 L h^{-1} located 25 cm on either side of the vine. Irrigation water was of good quality, with pH of 6.35, electrical conductivity of 163.4 µS cm^{-1} and 0.4 mg L^{-1} of suspended solids. The water amount applied each season was 40 and 50 mm for 2011 and 2012, respectively (Supplementary Table S.1).

2.3 Measurements

The volumetric soil water content was continuously monitored through the soil profile in two spots of the experimental vineyard (one in the rain-fed treatment and another in the irrigated treatment) using two capacitance probes (EnviroSCAN, Sentek, Australia), based on the frequency domain reflectometry (FDR) technique. Each probe was equipped with three sensors installed on an access tube at 20, 40 and 60 cm depth and connected to a datalogger. The probes were properly maintained for recording soil water content at half-hour intervals over the 2011 and 2012 seasons. Here, data from the irrigation period (mid-June to late-August) are reported.

In each treatment, the probe was located within two vines (Fig. 1), avoiding to be close to the emitters (25 cm from the emitter and 50 cm from the vine trunk, approximately). The equation provided by the manufacturer was used for transforming permitivity data registered by the probes into soil water content since we only wanted to compare relative contents between these two irrigation regimes. Previous work suggest that soil type greatly affects the FDR readings, but the default equation is valid for differential measurements (Paraskovas et al., 2012).

2.4 Multifractal analysis

The concepts of multifractals and their estimation methods that were used in the current study are next summarized. For detailed descriptions about multifractals, further information can be found in Chhabra et al. (1989) and Everstz and Mandelbrot (1992).

To implement the multifractal analysis of one-dimensional soil water content time distributions supported on a given interval I = [a, b], a set of not-overlapping sub-intervals of I with equal length is required. A common choice is to consider dyadic scaling down (Everstz and Mandelbrot, 1992; Caniego et al., 2005), which means successive partitions of I in k stages (k = 1, 2, 3…). Hence, at each scale, d, a number of segments, $N(\delta) = 2^k$ are obtained with characteristic time resolution, $\delta = L \times 2^{-k}$, covering the whole extent of I.

Multifractal approach applied to time series has already been described (Jiménez-Hornero et al., 2010), hence, we only summarize the technique used in the current study. The time interval of soil water content data series, L, varied from half an hour to two months and the minimum time resolution, δ_{ini}, was chosen accounting for containing at least one half-hourly averaged soil moisture data, θ_{ini}, at every initial interval. According to this, the probability mass distribution, $p_i(\delta)$, at time resolution δ was estimated as:

$$p_i(\delta) = \frac{\theta_i(\delta)}{\sum_j^{n_{ini}} (\theta_{ini})_j} \qquad (1)$$

where θ_i is the water content of the i^{th} interval and n_{ini} is the number of initial intervals with mean soil water content θ_{ini}.

The method of the moments was used (Chhabra et al., 1989) to analyze the multifractal spectrum of the probability mass function, $p_i(\delta)$. The partition function $\chi(q, \delta)$ was estimated:

$$\chi(q,\delta) = \sum_{i=1}^{n} p_i(\delta)^q \qquad (2)$$

were moment q is a real number between -∞ and +∞.

A log-log plot of the partition function versus δ for different values of q yields:

$$\chi(q,\delta) \propto \delta^{-\tau(q)} \qquad (3)$$

were $\tau(q)$ is the mass scaling function of order q. The functions $f(\alpha)$ and α can be obtained by Legendre transformation of the mass exponent, $\tau(q)$, as: $f(\alpha) = \alpha(q) - \tau(q)$ and $\alpha(q) = d\tau(q)/dq$, respectively. Log-log plots of $\chi_q(\delta)$, versus δ, however, typically exhibit linearity across a limited scale range (e.g. Posadas et al., 2003), which results in drawbacks when using the moment method to obtain the singularity spectrum.

The direct method (Chhabra and Jensen, 1989) avoids inaccuracies associated to the estimation of $\alpha(q)$ by Legendre transformation. This method is based on the calculation of the contributions of individual segments, $\mu_i(q,\delta)$, to the partition function, which are defined as:

$$\mu_i(q,\delta) = \mu_i^{\,q}(\delta) / \sum_{1}^{N(\delta)} \mu_i^{\,q}(\delta) \qquad (4)$$

Then, using a set of real numbers, q, ($-\infty < q < -\infty$), the relationships applied to calculate $f(\alpha)$ and α, can be expressed as:

$$f(\alpha(q)) \propto \frac{\sum_{i=1}^{N(\delta)} \mu_i(q,\delta)\log[\mu_i(q,\delta)]}{\log(\delta)} \qquad (5a)$$

and

$$\alpha(q) \propto \frac{\sum_{i=1}^{N(\delta)} \mu_i(q,\delta)\log[\mu_i(\delta)]}{\log(\delta)} \qquad (5b)$$

The $f(\alpha)$–α spectrum is reduced to a point for monofractal scaling type. The minimum scaling exponent ($\alpha_{\min}$) corresponds to the most concentrated region of the measure, and the maximum exponent ($\alpha_{\max}$) corresponds to the rarefied regions of the measure. A plot of $f(\alpha)$ vs. α is called multifractal spectrum. It is a downward function with a maximum at $q = 0$. The width of the multifractal spectrum ($w = \alpha_{max} - \alpha_{min}$) indicates overall variability (Moreno et al., 2008) similar to the nugget effects in geostatistics. For each data series, we calculated multifractal spectrum with q from −10 to +10 in steps of 0.5, fine enough to show the multifractal behaviour in the studied moment range.

Multifractal measures can also be characterized on the basis of the generalized dimension, D_q, of the moment of order q of a distribution, defined by Grassberger and Procaccioa (1983), based on the work of Rényi (1955). The D_q, of a multifractal measure is calculated as:

$$D_q = \frac{\tau(q)}{q-1} = \frac{1}{q-1} \lim_{\delta \to 0} \frac{\log[\chi_q(\delta)]}{\log \delta}, \quad q \neq 1 \qquad (6a)$$

and

$$D_1 \approx \lim_{\delta \to 0} \frac{\sum_{i=1}^{n(\delta)} \mu_i(\delta) \log[\mu_i(\delta)]}{\log \delta}, \quad q=1 \qquad (6b)$$

Equation (6a) shows that $\tau(q)$ is also related to the generalized fractal dimension, D_q. In fact, the concept of generalized dimension, D_q, corresponds to the scaling exponent for the q^{th} moment of the measure. Using equation (6a), D_1 becomes indeterminate. Therefore, for the particular case that q =1, equation (6b) was employed.

For a monofractal, D_q is a constant function of q. However, for multifractal measures, the relationship between D_q and q is described by a S-shaped curve. In this case, the most frequently used generalized dimensions are D_0 for q = 0, D_1 for q = 1 and D_2 for q = 2, which are referred to as capacity, information (or Shannon entropy) and correlation dimension, respectively. The information dimension, D_1, provides insight about the degree of heterogeneity in the distribution of the measure. The correlation dimension, D_2, is associated to the uniformity of the measure among intervals and describes the average distribution density of the measure. In general, the generalized dimension, D_q, is more useful for the comprehensive study of multifractals. Differences between D_q allow comparison of the complexity between measured soil water content data series. In homogeneous structures D_q are close, whereas in a monofractal they are equal.

3 Results and discussion

3.1 Patterns of vineyard soil water content under rain-fed and irrigation conditions

Temperatures for the two studied growing seasons were similar in average (Table 1); however, rainfall and evapotranspiration were higher in 2012. Harvest date was almost the same in both years. Nevertheless, the temporal evolution of rainfall and ET_c differed from year to year (Fig. 2), being greater during 2012, especially at the beginning of the study period. This fact caused a different scheduling of irrigation between years.

Soil water content decreased over the growing season under rain-fed conditions in both years (Fig. 3). However, when irrigation was initiated, soil water content became more stable in the irrigated treatment (Fig. 3). The magnitude of the soil water loss was more evident in the layers of 20 and 40 cm depth, and less important in the 60 cm layer, which may indicate the depth of the active root zone as well as the intensity of root water uptake at each soil layer, as reported for other cultivars and crops (Intrigliolo and Castel, 2009; Mestas-Valero et al., 2011), and proved that FDR probes can be successfully used for irrigation scheduling (Goldhamer et al., 1999), calibrating them with established indicators such as midday stem water potential (Mirás-Avalos et al., 2014) and soil evaporation. ~~Indeed, our results suggest that the water amount applied through irrigation was enough for fulfilling vineyard water requirements over the two growing seasons studied~~.

3.2 Multifractality of the soil water content time series

Soil water content time series obeyed power law scaling, as shown by the double log plots (Supplementary Fig. 4S.1). These plots allow to identify the range of moments needed to describe the scale variation of the studied parameter (Vidal Vázquez et al., 2010).

Figure 4 shows the partition functions for rain-fed and irrigation conditions at 20 cm depth in 2011. Visually, a slight departure from the straight line model was observed for moments $q <$ -1 (Supplementary Fig. S.41). In general, higher deviations from linearity were found for the highest q moments in the data series from the irrigation treatment, when compared to those from the rain-fed treatment, especially in 2012. Nevertheless, determination coefficients, R^2, were greater than 0.9 for statistical moments in the range from q = -10 to q = 10, in all the studied data sets. Consequently, scalings are adequately defined. Similar results were found by Mestas-Valero et al. (2011) for soil water content under rain-fed grassland.

The $\tau(q)$ functions were different from a monofractal type of scaling for all series analyzed, especially under irrigation conditions (Supplementary Fig. ~~5~~S.2), similar to results obtained by Biswas et al. (2012b) for soil water storage. In fact, the hetereogeneity of the soil water content data series from the irrigated treatment was greater than that of the rain-fed treatment (Supplementary Fig. ~~5~~S.2).

The value of D_1 is a good indicator of the heterogeneity degree in temporal distributions of a given variable. The closer the D_1 value to D_0, the more homogeneous is the distribution of the variable. In our case, rain-fed series were more homogeneous than the irrigated ones. In general, soil water content recorded at 60 cm depth presented the lower differences between D_1 and D_0 (Table ~~2~~1), thus being more homogeneous both under rain-fed and irrigation conditions. Moreover, 2012 data series presented a higher hetereogeneity than those from 2011 (Table ~~2~~1) for both treatments, caused by the greater rainfall amount collected in 2012.

A monofractal would be characterized by $D_0 = D_1 = D_2$ (Evertsz and Mandelbrot, 1992). In all the studied data series $D_0 > D_1 > D_2$ (Table ~~2~~1), indicating that soil water content had a tendency to behave as a multifractal. However, differences ($D_0 - D_1$) ranged from 0.051 to 0.222 and ($D_1 - D_2$) oscillated between 0.053 and 0.168, which suggests different degree in the homogeneity/heterogeneity of soil water content depending on the treatment imposed and the depth in the soil profile. In general, data series from the irrigation treatment showed greater differences between D_0, D_1 and D_2 than the series from the rain-fed treatment for both growing seasons. Moreover, the 60 cm depth layer presented smaller differences than the 20 and 40 cm layers (Table ~~2~~1). The width of the D_q spectra, determined by indicators such as ($D_0 - D_{10}$), showed different degrees of hetereogeneity, with a trend to decrease in depth and under rain-fed conditions when compared with the irrigation treatment (Table ~~2~~1). This is caused by the spiky nature of soil water content and indicates a multiple scaling nature at shallow depths. Moreover, the width of the D_q spectra increased from 2011 to 2012 in both treatments, mainly in the 20 and 40 cm depths.

Generalized dimensions, or Rényi spectra, calculated for the range between q = -10 and q = 10 for soil water content data series at three depths under rain-fed and irrigation conditions are displayed on Fig. ~~6~~4. All the data series studied showed Rényi spectra as asymmetric sigma-shaped curves with more curvature for the negative values of q than for positive ones

(Fig. ~~6~~4). The left part of the curves is concave down and it changes to concave up on the right of the vertical axis. In the case of the soil water content series from the rain-fed treatment, the most curved spectra corresponded to the 40 cm depth data series, whereas for the irrigation treatment, the most curved one was the 20 cm depth data series (Fig. ~~6~~4). When compared between treatments, Rényi spectra were more curved under irrigation conditions and the estimation errors were also greater under this treatment (Fig. ~~6~~4). These results confirmed the higher hetereogeneity (multifractality) of the data series from the irrigation treatment when compared to those from rain-fed.

Mestas-Valero et al. (2011) obtained monofractal distributions of soil water content time series under grassland when measured at depths greater than 40 cm, in contrast with our results. This disagreement is likely caused by the fact that grapevine root system reach greater depths than that of grass and vines are capable of uptaking water from deeper soil layers.

Determination coefficients, R^2, were highest for moments $q = 0$ and $q = 1$ and diminished for the other $|q|$ moments. In the case of $q = 10$, R^2 was greater than 0.97 and 0.95 in the rain-fed and irrigated data sets, respectively. For $q = -10$, R^2 values for rain-fed and irrigated data series were greater than 0.99 and 0.91, respectively (data not shown). Standard errors of D_q values increased with increasing $|q|$ moments and they were much lower for right ($q > 0$) than for left ($q < 0$) branch of the Rényi spectra (Fig. ~~6~~4).

Parameter α_0 from the singularity spectra ranged from 1.056 to 1.146 in the rain-fed treatment and from 1.075 to 1.187 in the irrigated treatment (Table ~~3~~2). The singularity spectrum allows for analyzing similarity or difference between the scaling properties of the measures as well as to assess the local scaling properties of soil water content measurements. The wider the spectrum is (i.e., the largest $\alpha_{q-} - \alpha_{q+}$ value), the higher the heterogeneity in the scaling indices and vice versa (Vidal Vázquez et al., 2010). Moreover, the $f(\alpha)$ spectrum branch length gives insight about the abundance of the measure. Hence, small $f(\alpha)$ values at the end of a long branch correspond to rare events. Our results showed that the width of the singularity spectra increased in both treatments from 2011 to 2012 (Table 2).

Singularity spectra are characterized by a concave down shape (Fig. ~~7~~5), showing an asymmetrical curve with wider but shorter right side. Rain-fed data series showed a shorter $f(\alpha)$ spectrum in both years, confirming their low degree of multifractality when compared to the irrigated data series (Fig. ~~7~~5).

Differences ($\alpha_{q-} - \alpha_0$ and $\alpha_0 - \alpha_{q+}$) indicate the deviation of the spectrum from its maximum value (q = 0) towards the right side (q < 0) and the left side (q > 0), respectively (Vidal Vázquez et al., 2010). Usually, soil water content data series from the rain-fed treatment showed lower $\alpha_0 - \alpha_{q+}$ values than those from the irrigated treatment (Table ~~3~~2). Moreover, the highest values for this multifractal parameter were observed at 40 cm depth in both treatments and years (Table ~~3~~2). This may indicate that higher soil water contents were more frequent under irrigation, being greater the differences between treatments at 40 cm depth in 2012. In contrast, the right branch ($\alpha_{q-} - \alpha_0$) of the spectrum was usually wider for rain-fed conditions (Table ~~3~~2). These results confirm the differential homogeneity/heterogeneity pattern between treatments evidenced by the generalized dimension, D_q, analysis (Table ~~2~~1, Fig. ~~6~~4).

4 Conclusions

Under the conditions of this study, continuous soil water content measurements at different depths reliable described the soil water balance in a vineyard over two irrigation periods.

The logarithms of the partition function varied linearly with the logarithms of the time resolution for all the studied depths under both treatments considered in the range of moments $-10 < q < 10$, indicating that soil water content time series obeyed power laws.

The scaling properties of soil water content time series were reasonably fitted to multifractal models. These properties were different for the rain-fed and irrigation treatments, implying a higher heterogeneity for the data series from the irrigation treatment, which tended to increase in the second year of the study (2012). Therefore, multifractal analysis allowed us to discriminate among soil water content patterns in a vineyard for the 2011 and 2012 growing seasons as a function of irrigation use.

Author contribution

J. M. Mirás-Avalos and E. Trigo-Córdoba designed and carried out the field experiment. J. M. Mirás-Avalos, R. da Silva-Dias, I. Varela-Vila and A. García-Tomillo performed the analyses. J. M. Mirás-Avalos prepared the manuscript with contributions from all co-authors.

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~~Table 1. Summary of climate variables (temperature, rainfall and ET_0), irrigation water applied and harvest date for the studied period in 2011 and 2012 (from 14th June to 26 August).~~

~~Year~~	~~Temperature (ºC)~~			~~Rainfall~~	~~ET_0~~	~~Irrigation~~	~~Harvest date~~
	~~Minimum~~	~~Maximum~~	~~Average~~	~~(mm)~~	~~(mm)~~	~~(mm)~~	
~~2011~~	~~12.44~~	~~28.86~~	~~20.15~~	~~25.60~~	~~230.78~~	~~39.67~~	~~14th September~~
~~2012~~	~~12.33~~	~~28.21~~	~~19.67~~	~~65.60~~	~~344.91~~	~~50.00~~	~~13th September~~

Table ~~2~~1. Selected multifractal parameters: generalized dimensions, for the first-three positive moments, D_0, D_1, and D_2, with their respective errors of estimation, and two multifractality indices $\Delta(D_0 - D_2)$ and $\Delta(D_0 - D_{10})$.

Treatment	Depth (cm)	D_0	D_1	D_2	$\Delta(D_0 - D_2)$	$\Delta(D_0 - D_{10})$
			2011			
Rain-fed	20	0.999 ± 0.001	0.937 ± 0.008	0.884 ± 0.016	0.115	0.672
	40	1.000 ± 0.000	0.881 ± 0.007	0.746 ± 0.014	0.254	0.752
	60	1.000 ± 0.000	0.925 ± 0.007	0.868 ± 0.013	0.133	0.656
	20-60	1.000 ± 0.000	0.916 ± 0.008	0.833 ± 0.019	0.167	0.589
Irrigated	20	0.999 ± 0.001	0.868 ± 0.013	0.778 ± 0.026	0.221	0.757
	40	1.000 ± 0.000	0.852 ± 0.019	0.773 ± 0.026	0.227	0.698
	60	1.000 ± 0.000	0.852 ± 0.022	0.758 ± 0.034	0.242	0.664
	20-60	1.000 ± 0.000	0.861 ± 0.023	0.773 ± 0.037	0.227	0.695
			2012			
Rain-fed	20	0.999 ± 0.001	0.861 ± 0.014	0.771 ± 0.025	0.228	0.856
	40	1.000 ± 0.000	0.888 ± 0.008	0.739 ± 0.017	0.261	0.801
	60	1.000 ± 0.000	0.949 ± 0.004	0.907 ± 0.005	0.093	0.548
	20-60	1.000 ± 0.000	0.898 ± 0.006	0.768 ± 0.016	0.232	0.682
Irrigated	20	0.984 ± 0.006	0.831 ± 0.010	0.731 ± 0.019	0.253	1.024
	40	0.979 ± 0.006	0.757 ± 0.014	0.589 ± 0.022	0.390	1.210
	60	1.000 ± 0.000	0.907 ± 0.007	0.805 ± 0.015	0.195	0.622
	20-60	0.993 ± 0.003	0.822 ± 0.016	0.707 ± 0.030	0.286	1.085

Table ~~3~~2. Selected multifractal parameters derived from the $f(\alpha)$ singularity spectra: most positive (q_+) and most negative (q_-) limits the range of multifractal scaling, Hölder exponent of order 0 (α_0), most positive (α_{q+}) and most negative (α_{q-}) exponents, widths of the let (α_0 – α_{q+}) and the right (α_{q-} - α_0) sides of the spectra.

Treatment	Depth (cm)	q_-	q_+	α_0	α_{q+}	α_{q-}	$\alpha_0 - \alpha_{q+}$	α_{q-} - α_0
				2011				
Rain-fed	20	-1.5	3.5	1.066	0.768	1.339	0.299	0.273
	40	-3.5	2	1.093	0.632	1.328	0.460	0.235
	60	-3.5	2	1.087	0.718	1.403	0.369	0.315
	20-60	-4	2	1.074	0.762	1.297	0.312	0.222
Irrigated	20	-2.5	2	1.136	0.714	1.450	0.422	0.314
	40	-4	3	1.160	0.664	1.383	0.496	0.222
	60	-5	2	1.132	0.700	1.333	0.435	0.200
	20-60	-4.5	2	1.142	0.709	1.375	0.433	0.233
				2012				
Rain-fed	20	-2.5	3	1.146	0.659	1.526	0.487	0.380
	40	-3.5	2	1.082	0.603	1.301	0.479	0.219
	60	-2	5.5	1.056	0.746	1.296	0.309	0.240
	20-60	-5	2	1.077	0.651	1.265	0.426	0.188
Irrigated	20	-0.5	2.5	1.164	0.602	1.361	0.562	0.197
	40	-1	1.5	1.187	0.575	1.491	0.611	0.304
	60	-4	2	1.075	0.716	1.223	0.360	0.148
	20-60	-1	2	1.172	0.624	1.489	0.548	0.317

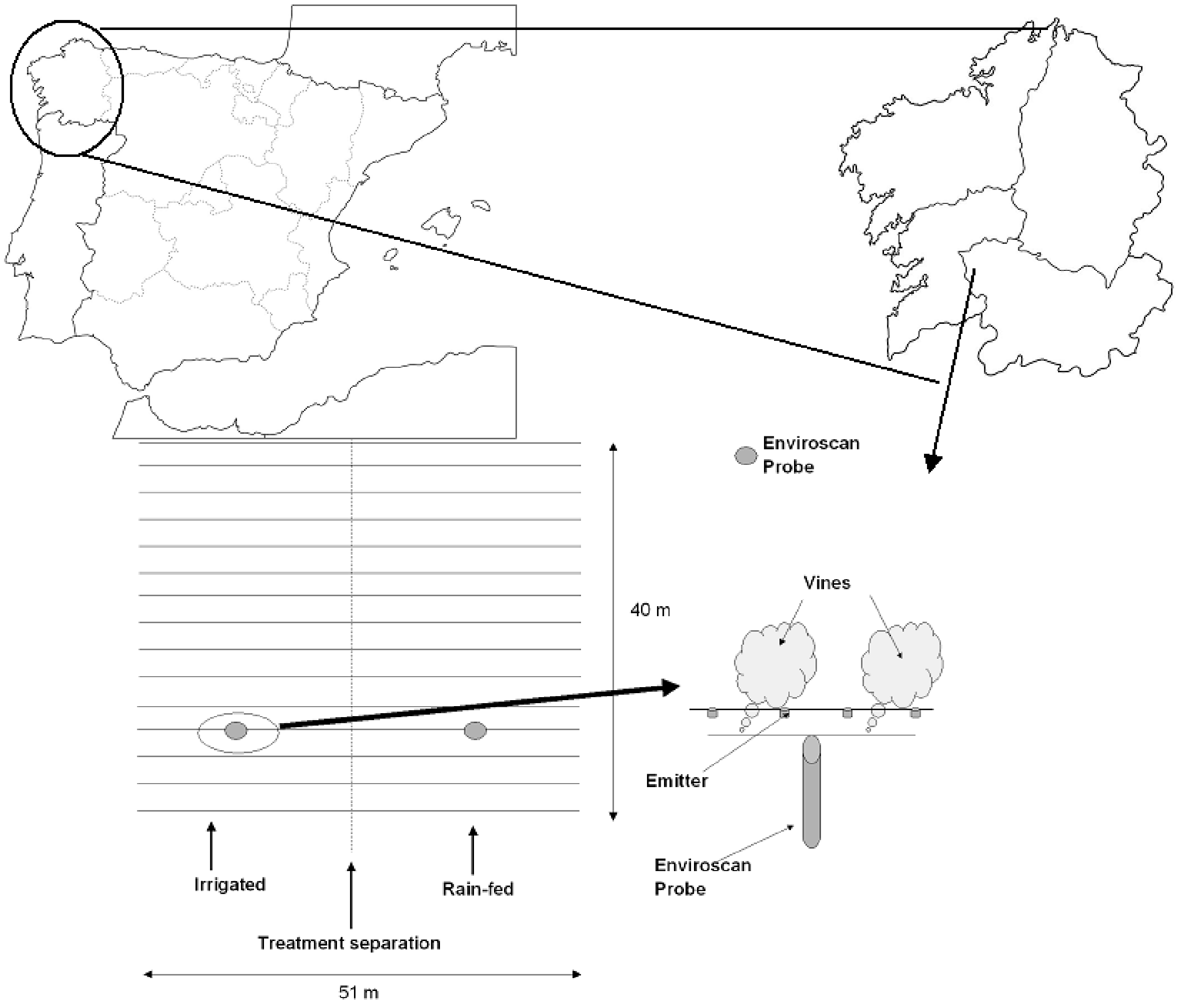


Figure 1. Location of the studied vineyard and experimental layout.

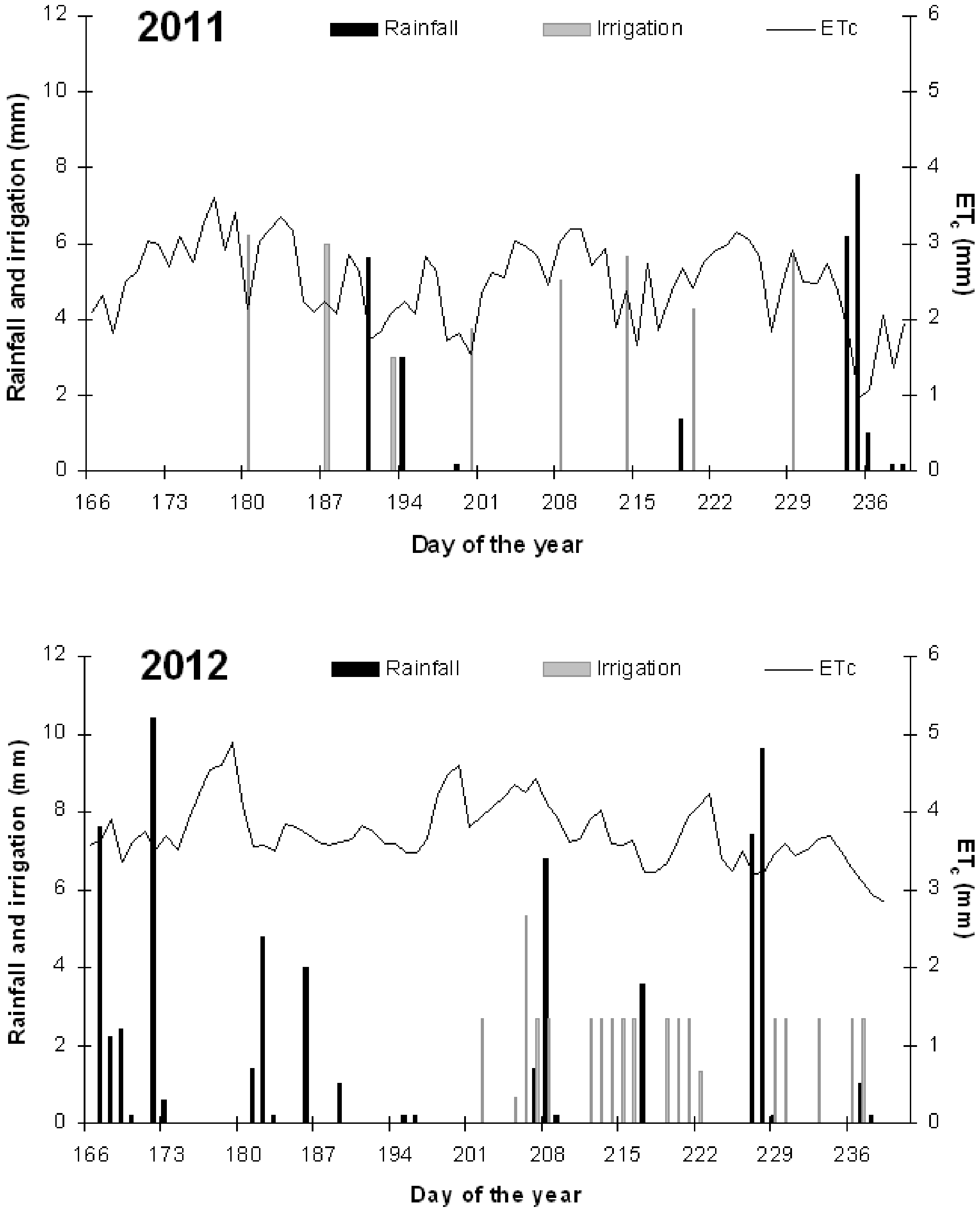


Figure 2. Crop evapotranspiration (ET_c), rainfall and irrigation water applied over the two growing seasons studied, 2011 and 2012. Day of the year 166 is 14th June.

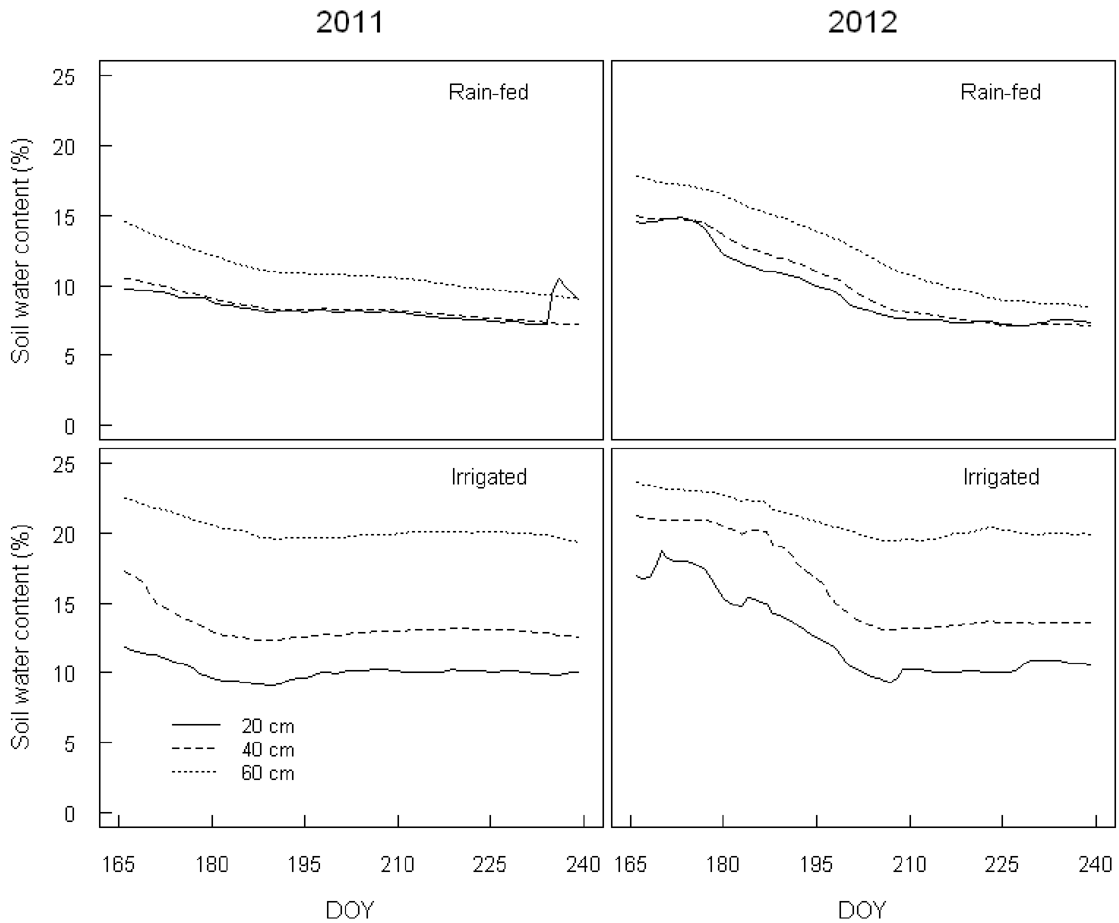
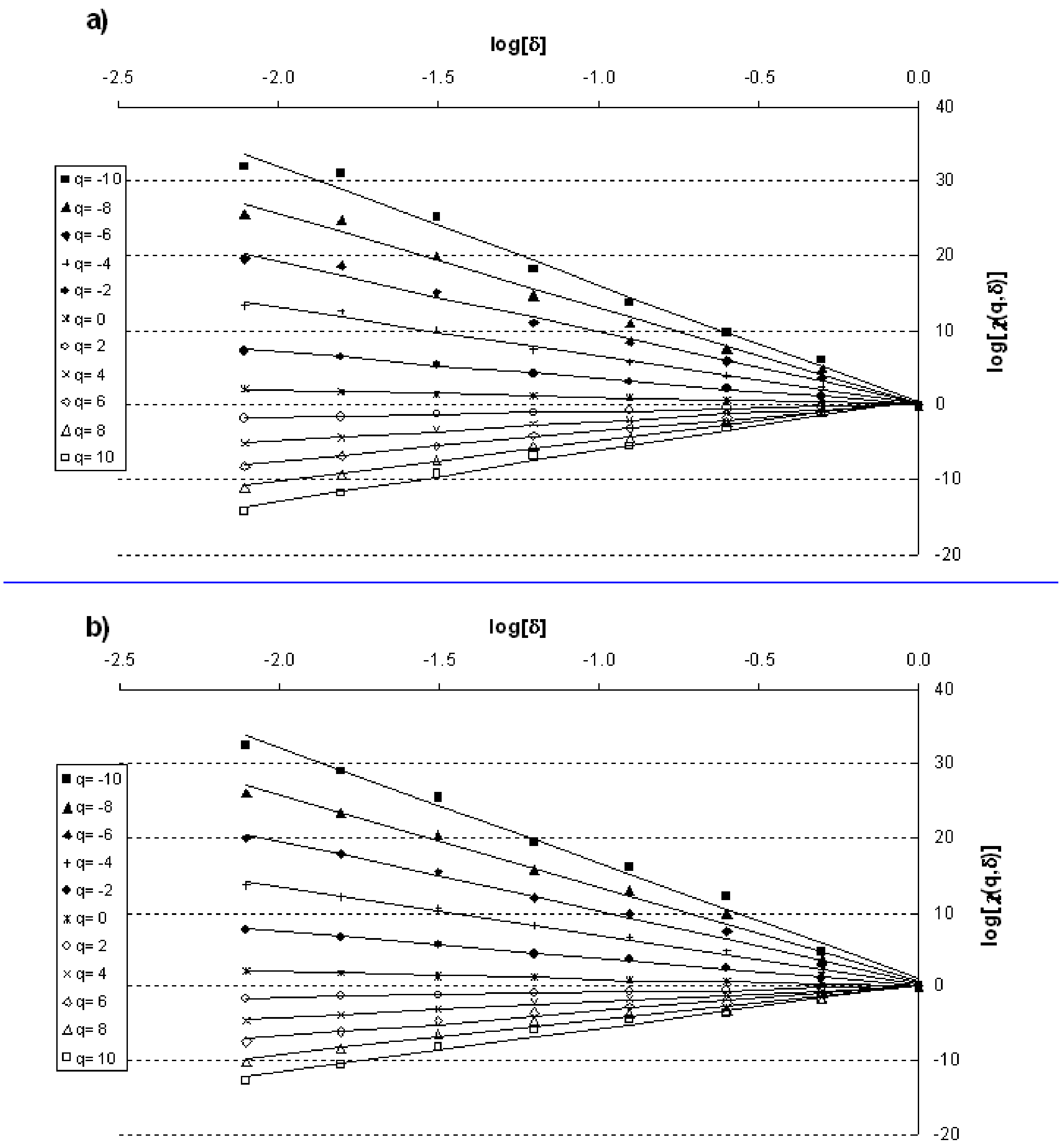
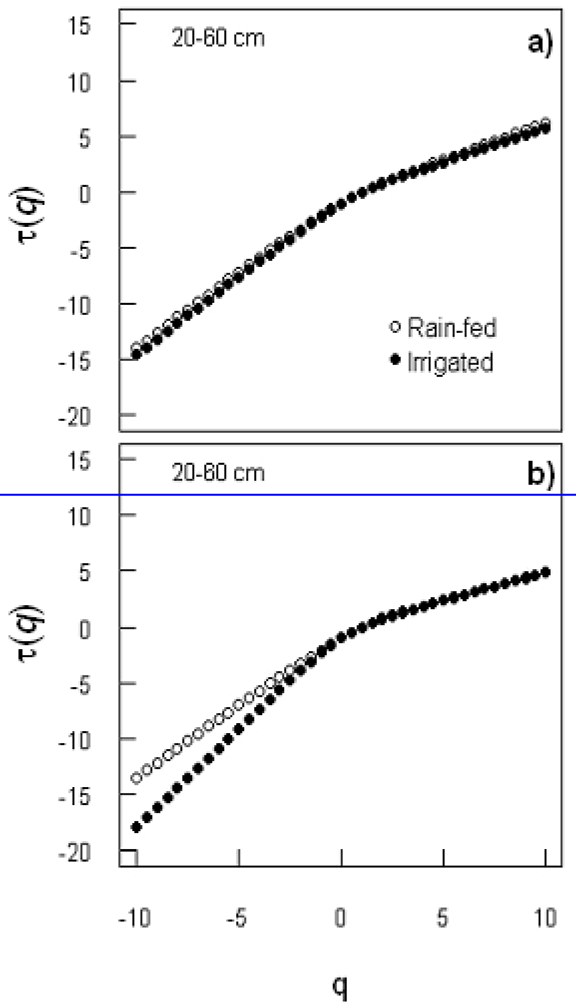


Figure 3. Soil water content at three depths (20, 40 and 60 cm) for rain-fed and irrigation treatments over the 2011 and 2012 growing seasons. DOY stands for Day of the Year (165 = 13th June).



~~Figure 4. Selected plots of the natural logarithms of the partition function, $\chi(q,\delta)$, versus the time resolution, δ. a) rain-fed treatment at 20 cm depth in 2011; b) irrigated treatment at 20 cm depth in 2011.~~



~~Figure 5. Mass exponents, $\tau(q)$, of soil water content averaged from 20 to 60 cm depth for rain-fed and irrigation treatments: a) 2011, b) 2012.~~

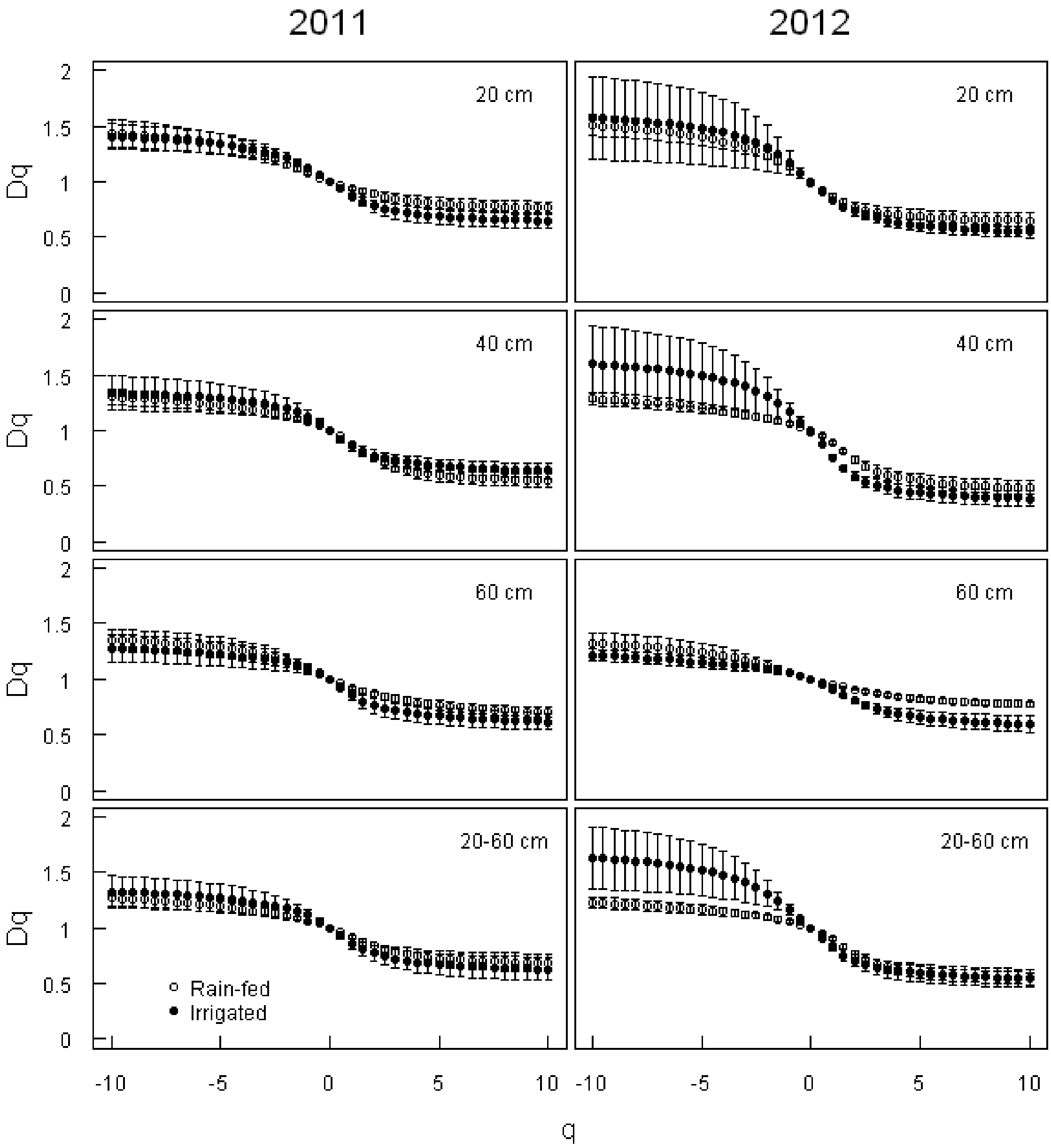
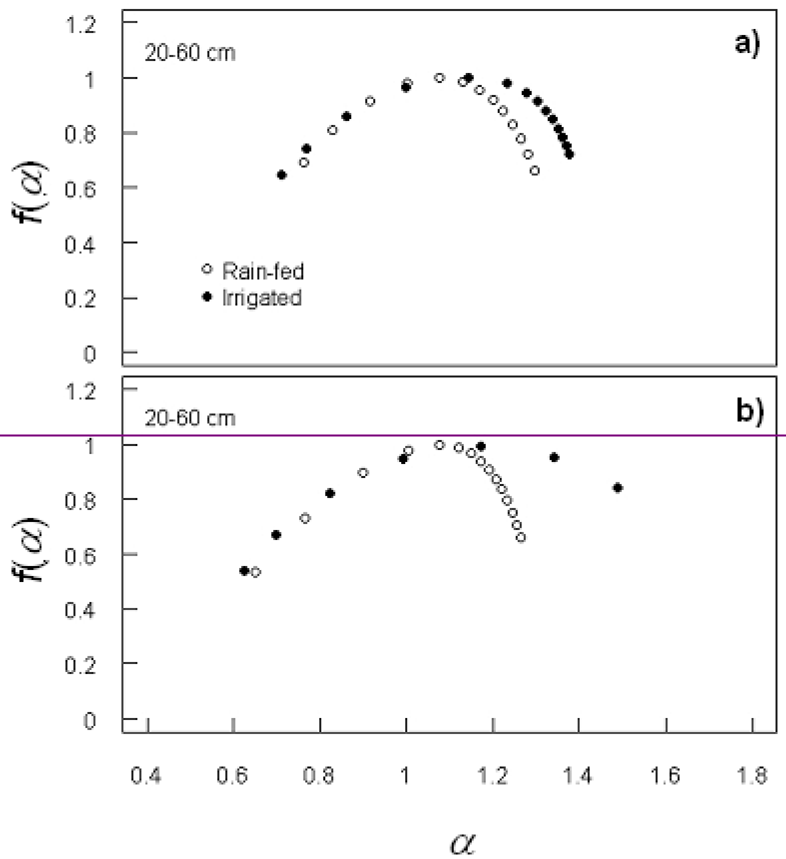


Figure ~~6~~4. Generalized dimension, D_q, spectra ($-10 < q < 10$) of soil water content for rain-fed and irrigation treatments at the studied depths in 2011 and 2012. Bars indicate estimation errors.



a)
20-60 cm
Rain-fed
Irrigated
b)
20-60 cm
f(α)
α

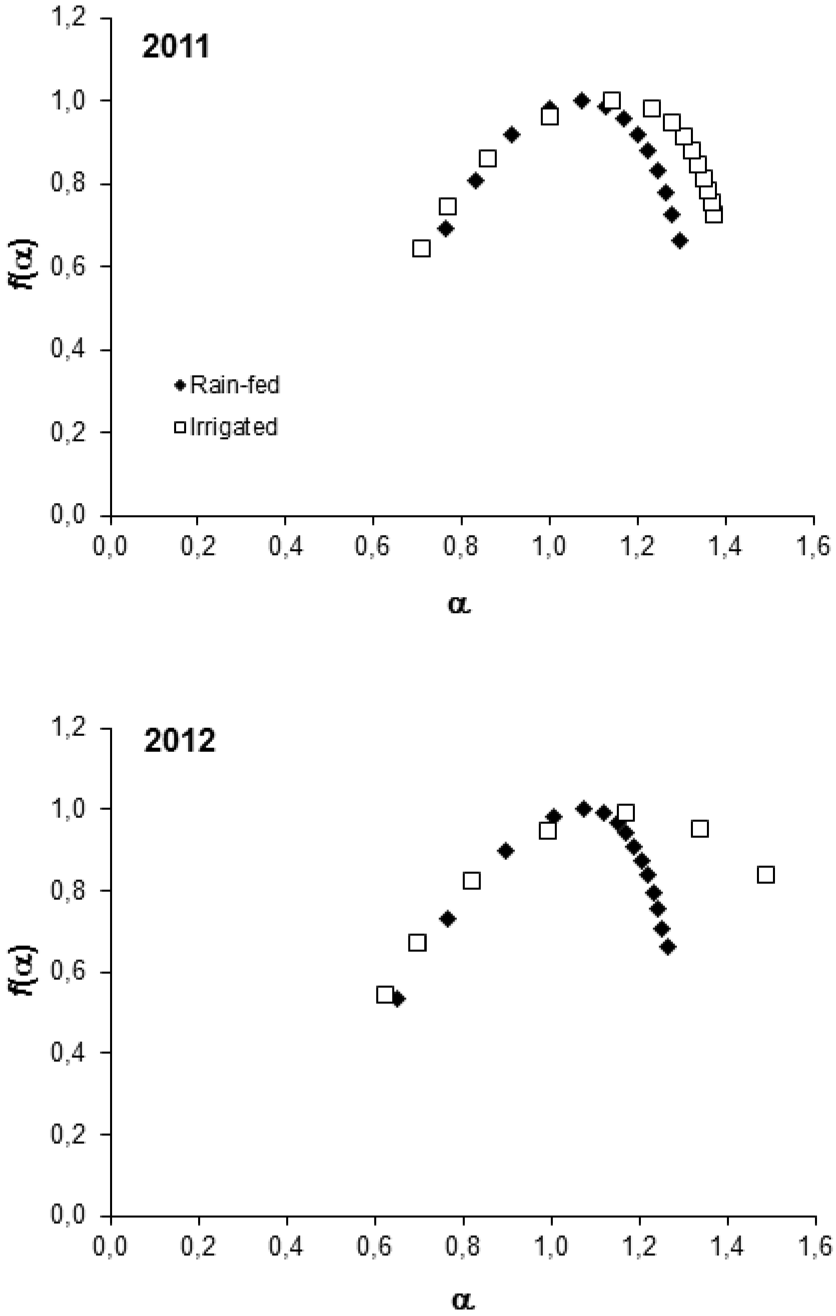


Figure ~~7~~5. Singularity spectra for soil water content averaged from 20 to 60 cm depth for rain-fed and irrigation treatments in 2011 and 2012~~: a) 2011, b) 2012~~.

Multifractal behaviour of the soil water content of a vineyard in NW Spain during two growing seasons. Mirás-Avalos et al. (Supplementary Materials)

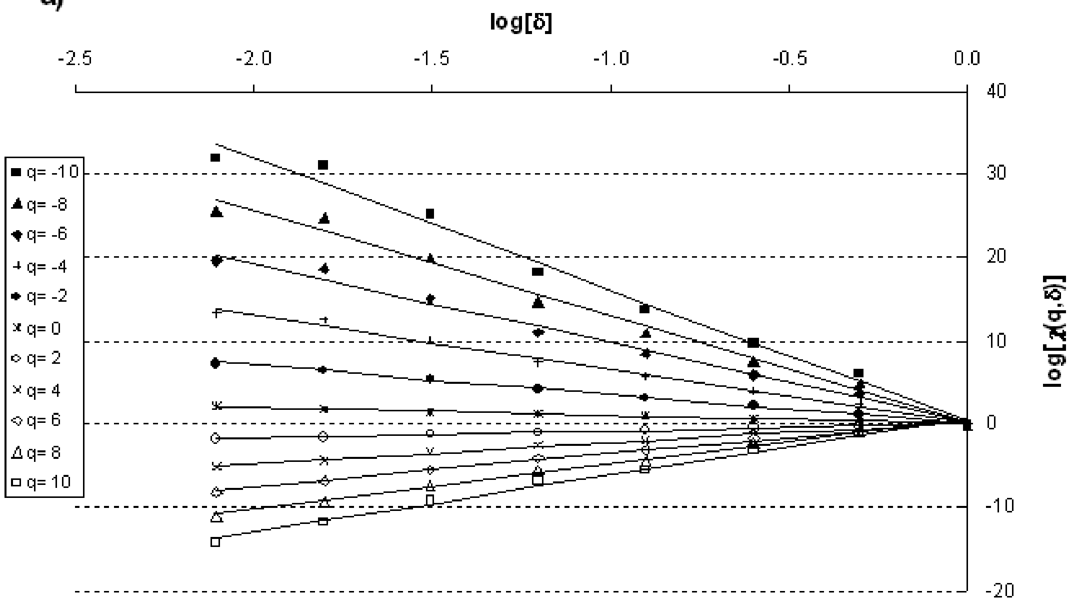
Supplementary information

Table S1. Summary of climate variables (temperature, rainfall, ET_0 and ET_c), irrigation water applied and harvest date for the studied and irrigation periods in 2011 and 2012.

		2011	2012
Measurement period		14 June to 26 August	14 June to 26 August
Temperature (ºC)	Maximum	28.86	28.21
	Minimum	12.44	12.33
	Mean	20.15	19.67
Rainfall (mm)		25.60	65.60
ET_0		230.78	344.91
ET_c		184.63	275.93
Irrigation period		9 July to 16 August	20 July to 22 August
Temperature (ºC)	Maximum	29.14	30.37
	Minimum	12.61	12.77
	Mean	20.36	20.82
Rainfall (mm)		10.20	29.20
ET_0		117.86	162.52
ET_c		94.28	130.02
Irrigation (mm)		39.67	50.00
Harvest date		14th September	13th September

Figure S1. Selected plots of the natural logarithms of the partition function, $\chi(q,\delta)$, versus the time resolution, δ: a) rain-fed treatment at 20 cm depth in 2011; b) irrigated treatment at 20 cm depth in 2011.

a)



b)

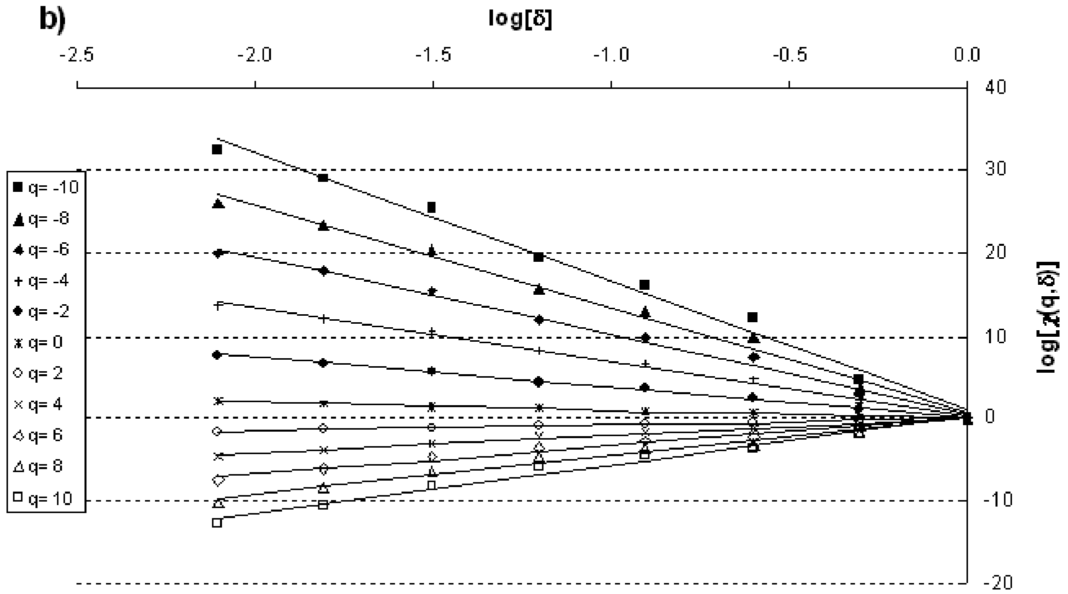


Figure S2. Mass exponents, τ(q), of soil water content averaged from 20 to 60 cm depth for rain-fed and irrigation treatments in 2011 and 2012.