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Title: Electromagnetic induction: a support tool for the evaluation of soil CO2 emissions and soil organic carbon content in olive orchards under semi-arid conditions

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Keywords: total soil respiration; EMI; ECa; SOC; soil sampling.

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Abstract: Electromagnetic Induction (EMI), a non-invasive geophysical technique, can be a useful tool to study soil distribution of physical-chemical characters that strongly influence total soil respiration. Soil respiration emission flux (FCO2) was followed in an orchard (0.7 ha) with olive trees placed at irregular distances. FCO2 was measured in four different days at 6:00 and 15:00 hours. Correlations between soil respiration and soil apparent electrical conductivity (ECa), the EMI output, were assessed. Statistically significant linear relationships were found between ECa, measured at 7 kHz, and FCO2 (R2 > 0.6). The strong relations found between daily FCO2 and ECa values allowed to spatialize soil respiration rate at field scale. The EMI technique combined with the statistical software called ESAP seemed to be a very efficient tool to choice representative soil sites within the field where to measure FCO2. The EMI/ESAP procedure was also compared with two soil sampling procedures, JRC-EU and regular grid sampling, in order to estimate average soil organic carbon (SOC) value within the olive orchard. Results suggested that the above mentioned approach could be an interesting solution to reduce number of samplings and their cost reaching, in the meantime, reliable assessments of FCO2 and SOC at field scale.

Matera, 16 July 2015
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To:
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Geoderma

Dear Editors,

please find attached the research paper entitled "Electromagnetic induction: a support tool for the evaluation of soil CO_2 emissions and soil organic carbon content in olive orchards under semi-arid conditions" by Egidio Lardo, Aissa Arous, Assunta Maria Palese, Vitale Nuzzo and Giuseppe Celano.

I warrant to You that the submitted manuscript describes original research not submitted for publication or already published elsewhere.

All the named co-authors agree to the work being sent out for peer-review and possibly published, and that they have no undeclared competing financial interests.

Yours faithfully,
Assunta Maria Palese

- Soil respiration (FCO_2) was performed in a heterogeneous olive orchard
- Significant relationships were found between FCO_2 and EMI signal (EC_a)
- Such relationships allowed to spatialize soil respiration rate at field scale
- EMI/ESAP procedure reduces costs providing representative soil sampling sites
- Different procedures for SOC assessment were compared

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Keywords: total soil respiration, EMI, EC_a, SOC, soil sampling

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Abstract

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1. Introduction

During the last decade the interest on soil CO_2 emission and carbon sequestration in terrestrial ecosystems has increased (Janssens et al., 2003; Smith, 2004) especially in the evaluation of temporal and spatial CO_2 soil fluxes. Soil respiration is the major source of CO_2 released by terrestrial ecosystems (Raich and Schlesinger, 1992) and it is used as a reference for calculating total greenhouse gases (GHGs) budget to better understand and quantify the emissions from soils (Allaire et al., 2012).

Soil CO_2 flux (FCO_2) consists in the gas release by respiration of plant roots and their related symbiotic microorganisms (autotrophic component), by soil microorganisms respiration (heterotrophic component) and by dissolved soil organic matter due to chemical reactions. FCO_2 may be influenced contemporarily by many factors such as climatic variables (humidity, temperature, radiation); soil biological, physical and chemical characteristics; agronomical management (tillage, irrigation, fertilization, manure application, pruning, plant phenology, etc.) (Bauer et al., 2006; Gregorich et al., 1998; Reth et al., 2005; Rochette and Angers, 1999; Sainju et al., 2008; Smith, 2003) and field morphology (Garrett and Cox, 1973; Hanson et al., 1993). The close interaction between the above reported variables influences consistently FCO_2 values and their evaluation in time and space becomes difficult due to the enormous variability of such parameters (Allaire et al., 2012).

This variability has long been studied and many methods have been tested in this way. However, to date, no specific method was defined as standard (Pumpanen et al., 2004). The chamber based method is used to measure FCO_2 on a small scale (Norman et al., 1992; Meyer et al., 1987), while portable instruments enable field spatial investigation of FCO_2.

The most critical aspect, especially in heterogeneous soils, is the definition of representative sampling points where to carry out the FCO_2 measurements. Usually, the number of sampling points is influenced and limited by labour costs and work time when portable instruments are used, by cost of instrumentations when the fixed chambers are employed (Adachi et al., 2005). Similarly, there are problems in defining the method of soil sampling to evaluate the content of soil organic carbon (SOC). Therefore, it is necessary to choose the degree of accuracy and representativeness of the space to consider. Soil sampling is normally conducted by classical methods (randomly, regularly grid) or by using the European sampling method (JRC-EU) proposed by Stolbovoy et al. (2007).

To reduce the number of sampling points, a stratified method can be used (Rodeghiero and Cescatti, 2008). Also, for a quick and reliable choice of the soil sampling design, a statistical approach, named EC Sampling, Assessment, and Prediction (ESAP) is proposed and developed by Lesch et al. (2002). Apparent electrical conductivity values (EC_a, see below) coming from geophysical field surveys are input of the ESAP software that uses the Response Surface Sampling Design (RSSD) statistical methodology to select a set of sample sites which optimizes the prediction model (Lesch et al., 2002). Using ESAP software a set of limited sampling sites (6, 12, or 20 sites) having desirable spatial and statistical characteristics can be selected (Hunsaker et al., 2009).

Another tool to study soil spatial variability is the electromagnetic induction technique (EMI). EMI, a non-invasive geophysical technique, can be used to study soil distribution of apparent electrical conductivity values (EC_a) (Corwin et al., 2003). EC_a is an integrated value of soil physical, chemical and biological properties: therefore, as the total soil respiration is a biological process it will be dependent by the same soil parameters as water content, soil texture, skeleton, temperature, clay content, organic matter content, etc.

Lardo et al. (2015) in a recent preliminary study, performed on vineyard field, found a strong relationship between EMI signal and FCO_2. The Authors hypothesized the use of EMI technique as a tool to choose field representative soil respiration measurement sites.

To verify and to improve these assumptions, relationships between spatial variation of EC_a and soil respiration were studied within a heterogeneous olive orchard located in Southern Italy. This research was carried out also to propose a methodology for choosing an adequate number of field representative FCO_2 measurement sites.

2. Materials and methods

2.1. The experimental site

The experimental olive orchard (*Olea europaea* L. - cv Maiatica) was located in Southern Italy (Miglionico - Matera Province, 40.554378 N; 16.515857 E) and it was grown under rainfed conditions. The climate is semi-arid with an annual precipitation of 574 mm (mean 1976-2009) and an average annual temperature ranging from 15 to 17 °C. Olive trees were about 30 years-old. They were irregularly planted on a sandy loam soil classified as *Eutric Cambisol* (Regione Basilicata, 2006). The olive orchard (0.70 ha) was located on a certain slope (3%) and its soil surface was entirely covered by spontaneous grasses mowed at least once per year.

2.2. Measurements of soil respiration, soil temperature and soil water content

Soil respiration flux (FCO_2), expressed as μmol CO_2 m^{-2} s^{-1}, were measured using a non-dispersive infrared gas analyser (Li-6400, LI-COR, Lincoln, NE, USA) equipped with a soil respiration chamber (Model Li-6400-09) which measures CO_2 concentration and determines the efflux by fitting the chamber to a polyvinyl chloride collar. A soil temperature sensor (PT105T) was attached to the equipment. A detailed description of the system functioning is reported in Pumpanen et al. (2004).

In order to study FCO_2 variability within the whole olive orchard, 20 polyvinyl chloride collars of 0.105 m in diameter and 0.10 m in height were inserted in the soil to the depth of 0.08 m at the nodes of a regular grid. Each node was distant from the others 39.4 ± 17.5 m. To evaluate the FCO_2 microvariability, other collars were placed at different distances (0.5, 1.5, 3, 5 m) from the trunk of three olive trees.

Each collar position was georeferred. In order to reduce a disturbance-induced CO_2 efflux, collars were installed at least 48 hours prior to the measurement campaigns. Herbaceous plants within the collars were cut and residues removed in coincidence of soil FCO_2 measurements. FCO_2 measurements were performed on 9^{th} and 20^{th} of October 2012 and on 9^{th} and 17^{th} of April 2013 at 6:00 and 15:00 hours which are the daily moments of minimum and maximum soil respiration rate. The average of the two measurements, for each sampling site, allowed us to obtain mean daily value of FCO_2 (Irvine and Law, 2002).

Soil temperature and soil volumetric water content (SWC) were measured at 0.15 m depth in coincidence of the FCO_2 measurements. In particular, SWC was measured by means of the Fieldscout TDR 300 soil moisture meter.

2.3. Electromagnetic induction measurements

Electromagnetic induction (EMI) surveys were carried out after each FCO_2 measurement with a multi-frequency EMI sensor (GSSI Profiler EMP-400). Such equipment can operate to measure simultaneously up to 3 frequencies between 1 kHz and 16 kHz, with intercoil spacing of 1.2 m. For this study, frequencies at 3, 7 and 14 kHz were chosen to collect information about different soil layers. The instrument was used in vertical dipole mode

(VDP). The depths of the magnetic field penetration were about 1.5 m for VDP modes (Allen, 2007). The instrument sensitivity varies as a non-linear function of depth (McNeil 1990). The apparent soil electrical conductivity (EC_a), expressed in mS m^{-1}, was used as EMI output. The instrument was calibrated according to its technical standards. Data were collected in continuous every 0.75 seconds. EC_a measurements were made walking at a speed of about 4-5 km h^{-1} in order to obtain a regular distribution of EMI signal in the field. Each acquisition was georeferenced by means of GPS. Data were processed by MagMap2000® and Surfer Golden® software in order to map EC_a values by linear kriging method. Anomalous EC_a data due to the iron gate that surrounds the property were not taken into account during the elaboration phase.

2.4 Soil samplings and soil analyses

A soil sampling was performed on 12 September 2012 following the regular grid technique. Twenty points were identified in coincidence of the nodes of the regular grid. As reported before, each node was distant from the others around 40 m and it was georeferenced. Three soil samples were taken from the 0-0.2 m layer in the area of competence of each node (1 meter of diameter) and then were mixed to form a single composite sample.

Another soil sampling was carried out the day after according to the JRC-EU procedure (Stolbovoy et al., 2007). Three sampling areas were identified within the olive orchard as function of its area (Stolbovoy et al., 2007). Soil samples were collected from the 0-0.2 m layer in coincidence of 75 points and then were mixed to form three composite samples (3 sampling areas x 25 sampling points).

To obtain an alternative and accurate sampling scheme for the identification of the most representative FCO_2 and SOC sampling points and the reduction of sampling labour and costs, the ESAP-EMI integrated procedure was used. This public statistical software, developed by the USDA-ARS ESAP-95 Version 2.35R (Lesch et al., 2000), uses the

Response Surface Sampling Design (RSSD) statistical methodology to select a set of sample sites which optimizes the prediction model (Lesch et al., 2002). In the present study, the ESAP-RSSD procedure was run twenty times in order to identify equivalent sets composed by 6 potential soil sampling points. After that, for each extraction the couples of potential and actual soil sampling points (these last obtained according to the regular grid procedure) which showed the minimum distance were identified. Among the identified twenty couple sets, that showing the mean minimum distance (4.1 ± 1.0 m, mean ± standard deviation) and the minimum sum of distances (24.7 m) was chosen to perform regression analysis on their EC_a values and the corresponding values of SOC and FCO_2.

Soil samples were air dried and sieved at 2 mm. On these samples the following analyses were carried out according to Pauwels et al. (1992): soil particle size analysis by means of the Andreasen pipette method; soil pH and electrical conductivity (EC_e) (soil: water, w w^{-1}, 1:1 ratio); SOC by the dichromate oxidation method.

2.5. Statistical and geostatistical analysis

Statistical analysis was performed using STATISTICA® 6.0 (Stat-Soft, Inc.; www.statsoft.com). Classical descriptors such as mean, maximum, minimum, standard deviation and skewness of data distribution were determined. ANOVA on average soil organic carbon content estimated by different procedures was performed. Univariate relationships between EC_a and soil respiration rate was studied by regression analysis.

The spatial variability dependence was analysed by applying geostatistical techniques using the VESPER® software 1.6 which follows the model reported in López-Granados et al. (2002):

$$y(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \quad \text{[eq. 1]}$$

where y(h) is the semivariance at separation distance h; N is the number of pairs separated by h distance; $Z(x_i)$ is the value of variable Z at point xi; and $Z(x_i + h)$ is the value of variable Z at point $x_i + h$. Plotting y(h) against h gives the semivariogram, which either exhibits purely random behaviour or some systematic behaviour described by theoretical models (linear, spherical, exponential, Gaussian, and power law models). Model coefficients were determined by the best fit to all the semivariance data. For variables that depended on separation distance, it was expected that the values of $Z(x_i) - Z(x_i + h)$ would increase with the distance h up to a given distance, after which point the values would stabilize. The distance in which the stabilization of semivariogram occurred, the range distance, was represented by α and defined as the spatial dependence limit. The C_1 value represented the structured spatial variability of data. The nugget effect, represented by the symbol C_0, is the semivariance value found at the intercept with the Y axis. The nugget effect represents the amount of variance not explained or modelled as spatial correlation. The semivariance value, called sill, is represented by the symbol $C_0 + C_1$ and is approximated similar to the variance of the analyzed data. The parameters C_0, $C_0 + C_1$, and α are currently used in semivariogram fitting equations to compare the spatial variability models of different studied soil parameters. The ratio between nugget effect and sill $C_0/(C_0 + C_1)$ or DSD was used to classify the spatial dependence of the studied properties, according to the work of Cambardella et al. (1994). As such, strong, moderate, or weak spatial dependence were considered to exist when $DSD \leq 0.25$, $0.25 < DSD < 0.75$, and $DSD \geq 0.75$, respectively.

Interpolation of measured EC_a was carried out using the kriging method (Surfer Golden Software® 8.0).

In order to identify univariate relationships among EC_a, FCO_2 rates and SOC, regression analysis was performed.

The strongest relationship found for EC_a *versus* FCO_2 was used to estimate FCO_2 data at field scale. The equation was the following:

$$FCO_{2\ \mathrm{estimated}} = EC_{a\ \mathrm{measured}} \cdot a + b \qquad \text{[eq. 2]}$$

ANOVA test (Tukey-Kramer test at $P < 0.05$) was performed among the SOC values resulting from the application of the three different sampling methods (regular grid, JRC-EU procedure and ESAP-EMI integrated procedure) in order to compare the effectiveness of the different methodologies on SOC estimation at field level.

3. Results

3.1. Spatial variability of soil physical and chemical characteristics

The least square procedure showed that stable and exponential semivariograms were the better models to describe spatial variability of physical and chemical soil parameters. Means, RSD, model and estimated parameters of experimental semivariograms obtained for sand, silt, clay, skeleton (g kg^{-1}), SOC (g kg^{-1}), pH, EC_e (μS cm^{-1}), FCO_2, soil temperature and soil water content are shown in Tables 1 and 2. The spatial distribution of sand followed the stable model while silt, clay and skeleton followed the exponential model. Texture and skeleton parameters showed a strong degree of spatial dependence (DSD) with values less than 0.25.

Soil pH was on an average 7.6±0.3 while EC_e and SOC were equal to 238±57 μS cm^{-1} and 7.8±2.1 g kg^{-1}, respectively (Table 1). The spatial distribution of these chemical parameters always followed the exponential model. SOC and pH showed a strong spatial dependence with degree values of < 0.25, while EC_e data showed a moderate DSD (0.47) (Table 1).

Mean values of FCO_2 measured within the olive orchard showed significant differences among the first measurement campaign performed on 9th of October (1.7 μmol m^{-2} s^{-1}) and the other campaigns which showed mean values around 4 μmol m^{-2} s^{-1} (Table 2). Generally, the spatial distribution of FCO_2 followed the exponential model showing a moderate degree of spatial dependence (Table 2).

The spatial distribution of soil temperature followed the Gaussian model (Table 2). The hottest day was the 9th October with a mean air temperature of 21.1 °C. The coldest day was the 9th April (mean air temperature = 15.0 °C). The DSD was strong for all the survey days except for 20th October (Table 2).

The spatial distribution of SWC did not show any spatial structure on both October dates whereas it followed the exponential and Gaussian models on 9th and 17th April, respectively (Table 2).

3.2. Soil temperature and SWC effects on FCO_2

At field level, relations between FCO_2, soil temperature and SWC were found but these were not particularly strong. The determination coefficients (R^2) of the above-mentioned variables ranged between 0.24 and 0.45 (regression on potential basis) (data not shown).

FCO_2, soil temperature and soil water content values measured at different distances from the tree trunk are showed in Figure 1.

At micro-variability level, a gradient of FCO_2 was found among measurement positions around the olive tree (Figure 1). The mean of FCO_2 values showed statistical significant differences at the different collar positions (ANOVA test). The FCO_2 value, measured at the distance of 0.5 m, exceeded 6.4 μmol m^{-2} s^{-1}, while for the other positions FCO_2 values did not exceed 3.5 μmol m^{-2} s^{-1}.

The temperature variation depending on the distance from the olive tree was not statistically significant and it ranged from 14.7 to 21.8 °C among the 4 distances (0.5 m, 1.5 m, 3.5 m, 5.0 m). Similarly, no correlation among SWC values and the distances from the trunk was observed.

3.3. FCO_2 *vs* EC_a, FCO_2 mapping and its representative measurement sites

The regression analysis showed a significant relationship between mean daily FCO_2 and mean EC_a values acquired at the different frequencies (14, 7, 3 kHz). An example of the relationship at 7 kHz (0.58 R^2) is shown in Figure 2 where at an increase of EC_a values corresponded a decrease of soil respiration values.

The equation obtained from the relation between EC_a and FCO_2 was used to spatialize the soil respiration rate at field scale. The derivate map of soil respiration within the experimental olive orchard is reported in Figure 3.

In order to define a possible minimum number of FCO_2 measurement sites within the orchard, the ESAP software was used as above indicated. Through this integrated procedure, again a strong relationship between EC_a and FCO_2 (0.73 R^2) was found by using just few measurements sites (6).

3.4. SOC *vs* EC_a and soil sampling procedures

No significant relationship was found by comparing SOC, measured in the 20 soil sampling points on the regular grid with EC_a values. On the contrary, a significant relationship (0.62 R^2) between EC_a and SOC measured on the sestet points chose by ESAP software was found.

According to the Tukey-Kramer ANOVA test, no significant differences were found among mean SOC values obtained from the three different methods used (regular grid method, JRC-EU method and ESAP-EMI integrated procedure) (Table 3).

4. Discussion

4.1 Spatial variability of soil parameters

The range of spatial autocorrelation for the soil physical and chemical parameters (Table 1) was similar to those observed by Kosugi et al. (2007) for tropical forests and by Allaire et al.

(2012) in arable fields. The degrees of spatial dependence of chemical and physical parameters were strong and followed stable and exponential models (Table 1). In particular, SOC and pH showed a strong degree of spatial dependence probably due to the position on a slope as suggested by De Figueiredo Brito et al. (2009). Risch and Frank (2006) found SOC auto-correlated values on soil samples taken at footslope where organic carbon content increase due to soil erosion processes.

FCO_2 and soil temperatures showed the same model of spatial variation during the measurements days. This phenomenon could be due to their relations with soil features stable in time. Moreover, SWC was more influenced by weather conditions occurred during the autumn and spring investigation periods (Table 2).

4.2 The influence of soil temperature and soil moisture on FCO_2

Several studies found strong positive correlations between FCO_2 and temperature (Fang and Moncrieff, 2001; Hashimoto et al., 2007; Herbst et al., 2009; Xu and Qi, 2001). In our study the spatial variation of FCO_2 was not completely close with temperature, indicating, that alone soil temperature cannot fully explain the field variation, as suggested by Zhang et al. (2013).

In fact, as found in our experimental field, soil temperature showed weak relations with FCO_2 probably due to its variability as an effect of the conditions made up by the spontaneous grass cover.

Curtin et al. (2012) showed a significant impact of SWC on FCO_2 in a specific soil moisture range. In the studied orchard, soil respiration increased after the 9th of October in coincidence of SWC increases due to consistent rain events (Table 2).

During all measuring days SWC did not show strong value of correlation with FCO_2. In this research, the weak impact of SWC on soil respiration could be related also to the depth of

SWC measurements (0.15 m). In semiarid climatic conditions the examined soil layer is strongly influenced by evaporation losses and then frequently inhospitable to microbial biomass which finds better conditions more in depth. The presence of weak relations between soil temperature, soil moisture and FCO_2 could be attributable also to the limited number of examined days which do not cover the entire temporal variability of the process.

FCO_2 highlighted wide variability at field scale, probably due to soil porosity and soil cracking, as suggested by Allaire et al. (2012), but also to the irregular disposition of olive trees resulting in a heterogeneity spaces with different carbon loading (senescent leaves, root decay).

According to Pumpanen et al. (2012), the variations in FCO_2 may be also affected by root and rhizosphere respiration, activity generally more concentred around the olive tree trunk. In particular, Figure 1 showed how FCO_2 was affected by the presence of the olive tree (greater respiration close to the trunk). At micro scale, FCO_2 were higher at the distance of 0.5 m from olive tree trunk than other more distant points (Figure 1). In the perennial orchard may occur what is called “island of fertility”. Near the trunk it can be created the better conditions of water availability and nutrition for heterotrophic microbial population and roots activity. This could explain the dependence of soil respiration on the distance from tree. Zhao et al. (2013) found that in a cotton field in central Asia, values of soil respiration under plants were larger than those beneath the gaps between rows of cotton plants. Lardo et al. (2015) in a vineyard found that TSR measured in the row position was approximately 35% higher than that recorded in the inter-row positions.

4.3. EMI and FCO_2 interactions and opportunities

La Scala et al. (2000) found that the spatial variability of FCO_2 was tied to soil properties as soil salinity and moisture (Balogh et al., 2011; Franzluebbers, 1999) which in turn affect EC_a

values. Furthermore, EC_a measured in some studies was highest for the fields with finer-textured soils and lower for the fields with coarser-textured soils (Sudduth et al., 2005).

Through the strong relationship between EC_a values and FCO_2 rates from soil (Figure 2), it becomes possible to evaluate the spatial variability of soil respiration. This operation could be useful to evaluate preventively soil spatial variability and identify homogeneous area where install the fixe equipment for long-term soil respiration measurements (Lardo et al., 2015). Soil EC_a may provide useful information for assessing variation in soil respiration. EMI technique seems to be a very efficient tool to locate representative soil sampling areas and spatialize CO_2 soil fluxes at field level (Figure 3).

The selection of opportune sampling sites saves time and work for the researcher and optimizes the evaluation model. The mean relation found between EC_a values and the selection of points extracted using ESAP-RSSD indicated how the procedure proposed could provide helpful information for sampling and for defining FCO_2 measurement sites within an orchard (Hunsaker et al., 2009).

4.4. Integrated procedure to SOC evaluation

As reported in Table 3, to evaluate SOC within the olive orchard, ESAP-EMI procedure did not show significant differences when compared to others common and accepted soil sampling methods (classical regular grid and JRC-EU method), defining six measure points as sufficient to achieve accurate estimates of parameters on fields of about one hectare. This can become an interesting solution to reduce the number of samplings and their cost also in time consuming.

5. Conclusions

This study evaluated the spatial variability of total soil respiration in a heterogeneous olive orchard located in Southern Italy. At field scale, our results showed the importance of spatial measures to define and determine accurate total soil respiration values within a certain period. The use of the EMI technique allowed to investigate soil spatial variability relating to its chemical-physical properties. EMI technique appears to be a very efficient tool to spatialize CO_2 soil fluxes at field level and to locate representative soil sampling areas. Therefore, ESAP method combined with the EMI technique seem to be reliable to estimate the mean value of SOC and they could become an effective strategy to reduce the number of soil samplings and, as a consequence, the cost of the evaluation procedure.

In the next years, these new methodologies and techniques should be increasingly used to evaluate spatial variability of soil biological processes and their evaluation at field scale.

However, more detailed studies on relations between soil electromagnetic responses and biological activities are needed especially in other pedoclimatic conditions and for other tree species.

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Table 1. Means, RSD, model and estimated parameters of the experimental semivariograms obtained for sand, silt, clay, skeleton (g kg^{-1}), soil organic carbon - SOC (g kg^{-1}), pH and electrical conductivity (μS cm^{-1}).

	Mean	RSD	Model	C_0	C_1	*a*	DSD	RMSE
Physical features								
Sand	540.6	0.07	*Stab*	737.0	50000	257.60	0.015	130.30
Silt	293.2	0.17	*Exp*	0.0	3381.4	15.02	0.000	202.80
Clay	86.6	0.23	*Exp*	38.0	679.3	21.44	0.053	56.66
Skeleton	79.6	0.81	*Exp*	124.2	5001.9	13.38	0.024	484.10
Chemical features								
SOC	7.8	0.27	*Exp*	0.9	11.2	167.50	0.074	0.33
pH	7.6	0.04	*Exp*	3790.3	50000	2231.7	0.070	194.20
Electrical conductivity	237.9	0.24	*Exp*	8495.2	9976.6	67.69	0.460	98.40

N=20; DSD: degree of spatial dependence = $C_0/(C_0+C_1)$, strong for values smaller than 0.25, moderate for values between 0.25 and 0.75; weak for values higher than 0.75 (Cambardella et al., 1994). *a*: minimum distance point not auto-correlated; RSME: Root mean square error; Exp: Exponential; Stab: Stable.

Table 2. Means, RSD, model and estimated parameters of the experimental semivariograms obtained for soil CO_2 flux (FCO_2) (µmol m^{-2} s^{-1}), soil temperature (°C) and soil volumetric water content (%) in the olive orchard during the different sampling days.

	Mean	RSD	Model	C_0	C_1	*a*	DSD	RMSE
FCO_2 (µmol m^{-2} s^{-1})								
9 Oct	1.71	0.47	*Exp*	0.20	0.54	18.38	0.273	0.06
20 Oct	4.34	0.42	*Exp*	1.42	2.39	17.80	0.373	0.35
9 Apr	4.78	0.36	*Exp*	0.96	2.11	12.07	0.312	0.21
17 Apr	3.85	0.34	*Exp*	0.75	1.11	16.66	0.404	0.08
Temperature (C°)								
9 Oct	21.14	0.05	*Gaus*	0.14	1.94	17.67	0.068	0.19
20 Oct	17.45	0.07	*Gaus*	0.58	2.26	5.92	0.205	0.32
9 Apr	15.01	0.14	*Gaus*	0.12	18.10	33.69	0.007	2.57
17 Apr	15.84	0.11	*Gaus*	0.15	9.76	23.02	0.015	2.17
SWC (%)								
9 Oct	5.99	0.23	*NE*	-	-	-	-	-
20 Oct	21.26	0.27	*NE*	-	-	-	-	-
9 Apr	24.52	0.33	*Exp*	0.00	66.99	8.41	0.000	8.19
17 Apr	17.23	0.35	*Gaus*	27.63	10000	1512.40	0.003	4.56

N=20; DSD: degree of spatial dependence = $C_0/(C_0+C_1)$, strong for values smaller than 0.25, moderate for values between 0.25 and 0.75; weak for values higher than 0.75 (Cambardella *et al*., 1994). *a*: minimum distance point not auto-correlated; RSME: Root mean square error; Exp: Exponential; Stab: Stable; Gaus: Gaussian; NE: Nugget effect.

Table 3. ANOVA test (Tukey-Kramer test at $P < 0.05$) between soil sampling methods performed to obtain accurate values of soil organic carbon (g kg^{-1}).

Method	*Soil Sampling (n)*	*Soil Analysis (n)*	*Soil Organic Carbon*					
			mean	min	max	variance	SD	CV
Regular grid sampling	60	20	7.81 a	3.22	11.51	4.49	2.12	0.27
European method	75	3	7.32 a	6.57	7.86	0.45	0.67	0.09
ESAP-EMI method	18	6	8.70 a	7.80	9.70	0.65	0.82	0.09

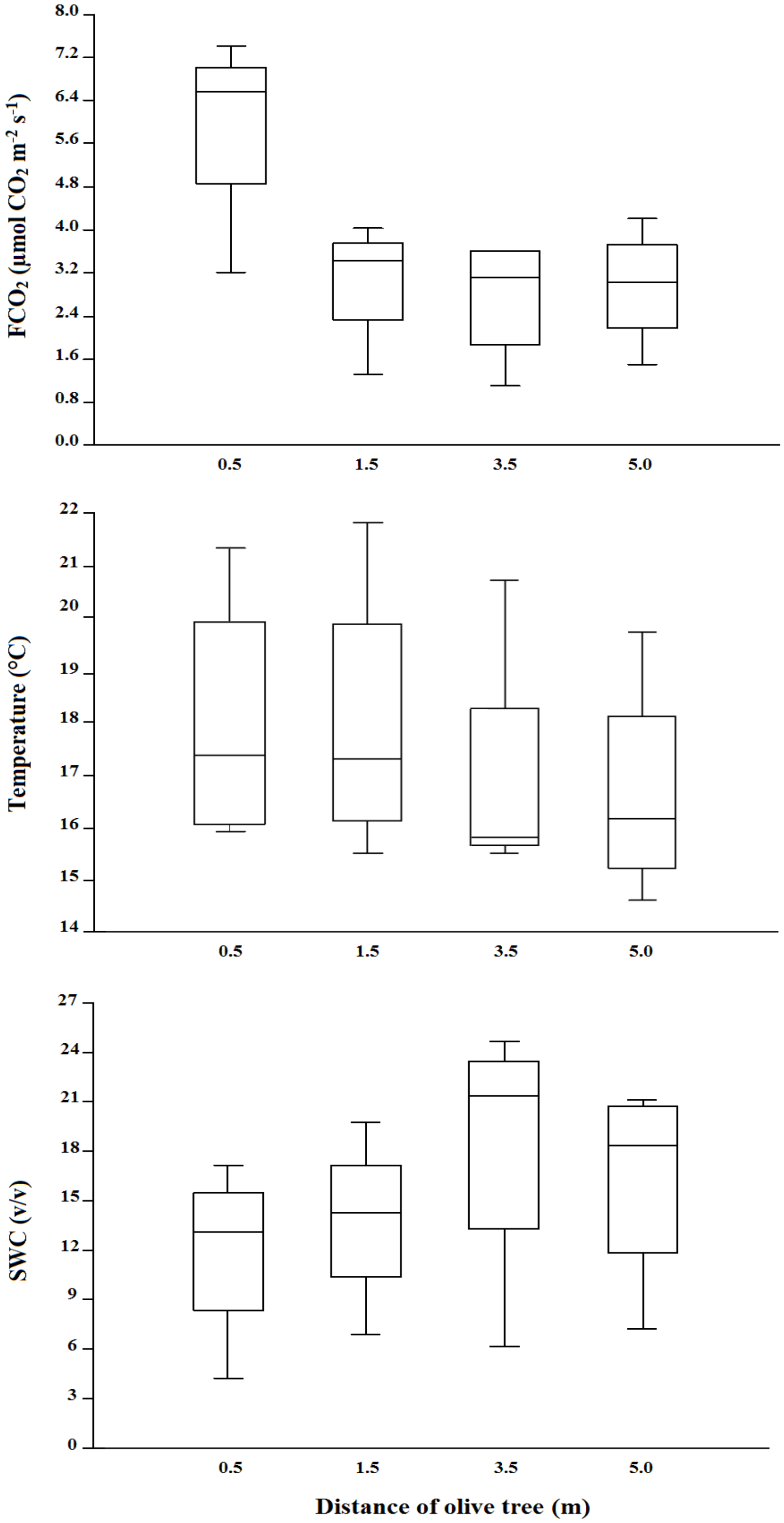
(n) is the number of soil sampling and analysis. SD and CV are, respectively, the standard deviation and the coefficient of variation.

FIGURE CAPTIONS

Figure 1. Variation of soil CO_2 flux (FCO_2), temperature and soil water content depending on the distance between the sampling points and the olive tree.

Figure 2. Relationship between soil apparent electrical conductivity (EC_a) at 7 kHz and soil CO_2 flux (FCO_2).

Figure 3. Map of soil CO_2 flux (FCO_2) and its variation at field scale.


8.0
7.2
6.4
5.6
4.8
4.0
3.2
2.4
1.6
0.8
0.0
FCO2 (µmol CO2 m-2 s-1)
0.5
1.5
3.5
5.0
22
21
20
19
18
17
16
15
14
Temperature (°C)
0.5
1.5
3.5
5.0
27
24
21
18
15
12
9
6
3
0
SWC (v/v)
0.5
1.5
3.5
5.0
Distance of olive tree (m)

1

2 FIGURE 1

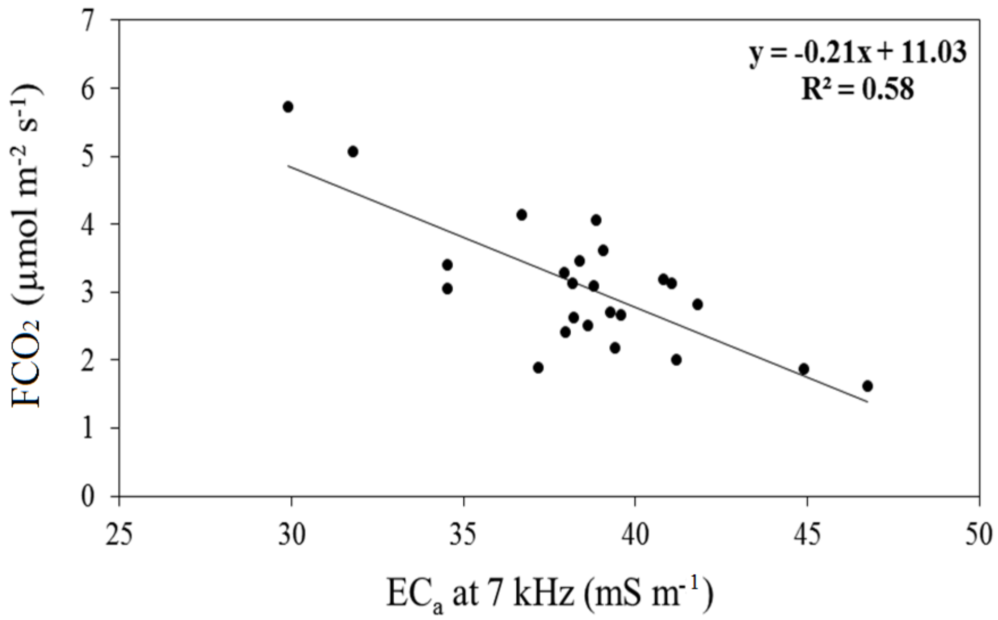

y = -0.21x + 11.03
R² = 0.58
FCO2 (µmol m-2 s-1)
ECa at 7 kHz (mS m-1)
0
1
2
3
4
5
6
7
25
30
35
40
45
50

FIGURE 2

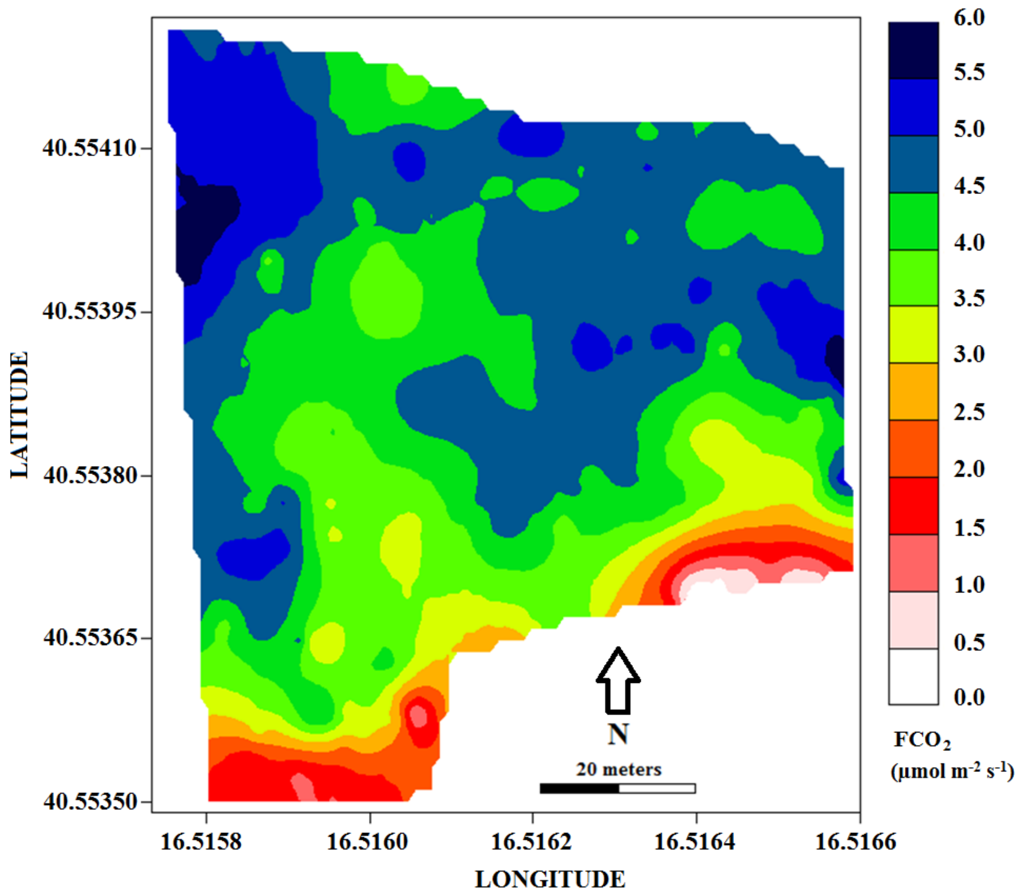

LATITUDE
40.55410
40.55395
40.55380
40.55365
40.55350
LONGITUDE
16.5158
16.5160
16.5162
16.5164
16.5166
N
20 meters
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
FCO2
(µmol m-2 s-1)

FIGURE 3

KML File (for GoogleMaps)

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