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Total soil respiration (TSR) is the major component of the CO_2 global flux. It is hard to define a TSR field value because this parameter shows high variability in time and space. An accurate TSR estimate could be the key to define soil CO_2 emissions. Electromagnetic induction can be useful to study the distribution of TSR field variability allowing an accurate accounting of soil efflux.

Variability of total soil respiration in a Mediterranean vineyard

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Abstract

Total soil respiration (TSR) is the major component of the CO_2 global flux. The knowledge of the temporal-spatial variability of TSR allows for a better interpretation of a critical component of global greenhouse gas flux measurements.

The objective of the research was to evaluate the TSR dynamic over a long measurement period in a vineyard in the South of Italy. A static home-made automatic system was used to measure TSR for a three years period. A portable gas analyser (Li-Cor 6400-09) was used to study TSR spatial variability. A non-invasive geophysical technique (Electromagnetic Induction - EMI) was applied to search for a significant relationship between apparent soil electrical conductivity (EC_a), the EMI signal, and TSR.

Long term measurements of TSR enabled to study its temporal dynamics. CO_2 rates ranged from 0.78 to 43.7 g CO_2 m^{-2} d^{-1}. TSR increased during spring and decreased by 45-50% during the mid-summer. The daily trend of TSR showed differences between the seasons studied reporting a clearly variation among TSR measured on row and inter-row positions. The supplemental irrigation significantly affected ($P < 0.001$) CO_2 soil effluxes which showed a weekly mean increase of 300%. Significant inverse relationships were found by interpolating TSR values and EC_a (coefficient of correlation ranging from -0.43 to -0.83 at $P < 0.001$). The spatialization of TSR at field scale was performed using the linear regression between TSR values and EMI signals.

TSR spatialization gave a more detailed view of CO_2 emissions distribution within the vineyard. EMI technique could be a useful tool to compute accurately the global CO_2 emissions which are a complex and hard to measure component of the agrosystem carbon balance.

Keywords: Soil Carbon Flux, Electromagnetic Induction, EC_a, Aglianico, Li-Cor 6400-09, Profiler EMP 400 GSSI.

Introduction

In recent years there has been an increasing interest in the carbon cycle in terrestrial ecosystems (Janssens et al., 2003; Smith, 2004), particularly in the understanding and portioning of the temporal-spatial variation in carbon fluxes. This knowledge can allow a more accurate prediction of how each carbon source and sink will respond to climate changes. Soils store the largest carbon pool in terrestrial ecosystems (Schlesinger, 1997) and the fate of such a pool depends ultimately on the balance between processes controlling soil carbon input and output (Delle Vedove et al., 2007).

Total soil respiration (TSR) (CO_2 fluxes from the soil) represents the critical link in the cycle of elements between autotrophic organisms, which reduce CO_2 to form organic compounds, and heterotrophic organisms, which oxidize organic compounds to release CO_2 (Rochette et al., 1997). TSR is a general definition for many important processes including respiration by live roots and associated mycorrhizae as well as by soil heterotroph, and chemical oxidation of plant detritus such as roots, leaves, woody inputs, root exudates, and humified organic matter. All these processes lead to the release of CO_2 through the surface of the soil (Masyagina et al., 2006).

TSR rate may be influenced contemporarily by many factors such as climatic variables (temperature, radiation), biological, physical and chemical characteristics of soil, and cultural practices (tillage, irrigation and pruning, plant phenology, etc.) (Buchmann, 2000; Gardenas, 2000; Raich and Tufekcioglu, 2000; Maestre and Cortina 2003; Weatherly et al., 2003; Ma et al., 2005; Wahren et al., 2005; Fernandez et al., 2006; Jarvis et al., 2007; Almagro et al., 2009).

TSR can be highly variable on diurnal, seasonal and interannual time scales and exhibits high levels of spatial heterogeneity (Savage and Davidson, 2001; Xu and Qi, 2001). There are several possible causes of this large heterogeneity, including soil-layers variability in the amount and activity of roots, litter availability and thickness, texture, soil bulk density, soil micro and macroporosity, soil moisture, soil organic carbon (SOC) and its labile fraction, C/N ratio, soil salinity, soil temperature (Epron et al., 1999; Buchmann, 2000; Gardenas 2000; Dominy et al., 2002; Ma et al., 2005; Søe and Buchmann, 2005; Fernandez et al., 2006; Jarvis et al., 2007; Almagro et al., 2009; Laik et al., 2009; Panosso et al., 2011; Allaire et al., 2012; Mavi et al., 2012; Bicalho et al., 2014). Therefore, the assessment of the temporal and spatial variability of TSR is the key for the understanding of CO_2 dynamics and for an accurate estimation of the agrosystem carbon balance at field scale.

Soil CO_2 fluxes can be measured by a variety of techniques but, at the present stage, no single method has been established as a standard (Pumpanen et al., 2004).

In order to better understand the processes influencing CO_2 emissions from soils and to handle their spatial and temporal heterogeneity, long term continuous measurements, based on automatic soil respiration systems, are required (Delle Vedove et al., 2007). Electromagnetic Induction (EMI), a non-invasive geophysical technique, can be useful for studying the distribution of soil physical-chemical characters affecting TSR. Indeed, the measurement of the apparent soil electrical conductivity (EC_a) by EMI has become an invaluable tool for identifying the spatial variation of soil physical-chemical properties (Corwin and Lesch, 2003; Doolittle et al., 2001; Davies 2004; Morari et al., 2009; Tromp-van Meerveld and McDonnell, 2009). EC_a is affected by several factors, the same which influence TSR: soil water content, soil texture, skeleton, temperature, clay content, mineralogy, cation exchange capacity, organic-matter content, and bulk density (Rhoades et al., 1999; Bronson et al., 2005; Chen et al., 2004; Corwin and Lesch, 2003; Domsch and Giebel, 2004; Friedman, 2005). Among the above mentioned factors, texture, soil water and salt contents are the most important influencing EC_a (Domsch and Giebel, 2004, Lück et al., 2009, Lai et al., 2012).

The aim of the present study was to evaluate the TSR dynamic during a long measurement period in a Mediterranean vineyard managed according to sustainable agricultural techniques (cover crops, no tillage, compost amendment, mulching). Furthermore, we speculated that TSR was constantly linked to EC_a as an EMI measurement output. Based on this assumption, a map of TSR variability at the vineyard scale, useful to carefully account for the global CO_2 emissions from agrosystems, could be quickly created through EMI measurements.

Materials and methods

Research scenario

The experimental vineyard (1.5 ha) was located in Montalbano Jonico (MT), Southern Italy (40° 19’ 22’’ N; 16° 33’ 39’’ E). The climate was semi-arid with mean annual precipitation equal to 525 mm and mean annual temperature ranging from 15°C to 17°C. The vineyard (*Vitis vinifera* L. cv. Aglianico grafted on 1103 Paulsen) was planted in 2005 and trained to a spur cordon (spaced 0.9 in the row and 2.5 m between rows; 4,444 vines ha^{-1}). The soil of the experimental site is a Chromi-Luvic Kastanozems (IUSS WRB, 2006). Soil physical and chemical characteristics are reported in Table 1.

From March 2009 to October 2011, the soil of the vineyard was not tilled but cover cropped with spontaneous species (*Avena fatua spp*., *Calendula officinalis* L., *Petroselinum crispum*, *Carlina hispanica* Lam., *Chondrilla juncea* L., *Scandix pecten-veneris* L., *Borago officinalis* L., and other minor species). Spontaneous crops were cut three times per year (in March, May and October) and mulched jointly with the pruning material. Soil was amended by compost (15 t ha^{-1} fresh weight; Eco-Pol Spa, VR, Italy) in March 2009 and 2010 (Table 2). Vineyard nutrient needs for both micro and macroelements were satisfied by compost application and crop residue recycling. Pest and disease control was performed according to the suggestions of the Regional Service (ALSIA - Agenzia Lucana di Sviluppo e di Innovazione in Agricoltura) which monitored weather conditions (air temperature, precipitation, evapotranspiration, etc.) by means of a meteorological station located in the experimental area. During the three experimental years, a single supplemental drip irrigation (33 mm) was carried out the 6th of August 2009. During the irrigation, soil moisture (% v v^{-1}) was measured by the gravimetric method on soil samples taken at 0-0.3 m depth.

Apparatus and techniques

TSR measurements

Two different apparatus were used to measure TSR: a portable system and a static multi-chamber automatic system (prototype). The former consists of 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. Soil temperature was measured using an attached soil temperature sensor (PT105T). A detailed description of the system functioning is reported in Pumpanen et al. (2004). The latter is a home-made closed dynamic system consisting of eight soil respiration chambers. A single chamber consists of a steel collar (0.3 m in diameter and 0.2 m in height), a chamber lid, and a motor to open and close the lid. The system was powered by two car batteries of 12 DC Volt and 60 Ampere. During field measurement activities the batteries were replaced and recharged every four/five days. Polyethylene tubes (15 m long, 4/6 mm inner/outer diameter) allowed the air sampling from the center of the chamber and its return after the measurement. A pressure vent was installed over the top of the chamber to avoid the air pressure difference between inside and outside, as indicated by Xu et al. (2006). During the measurement, air circulated between the soil chamber to an infrared gas analyzer (IRGA, SBA-4, PP-Systems) at a constant flow rate (0.5 L min^{-1}). A datalogger (CR1000, Campbell Scientific Inc. Lincoln Nebraska - USA) with a 16 channel AC/DC controller (SDM CD16-AC, Campbell Scientific) electronically managed the opening and closing of the chambers. Atmospheric CO_2 accumulated in the chamber was measured as μmol CO_2 mol^{-1} of dry air, every two seconds during the closure. The closure chamber time was of 150 seconds and data registration was performed between 40 and 120 seconds. TSR values were computed using the following equation (eq. 1) (Welles, et. al., 2001) and expressed as g CO_2 m^{-2} h^{-1}:

$$TSR = \frac{C_{vol}}{GS(T_{air} + 273.15)} \frac{dC}{dt} \qquad \text{eq. [1]}$$

considering air temperature (T_{air}) (measured every fifteen minutes by a 50Y sensor attached to the instrument), universal gas constant (G) (8.31 J mol^{-1} K^{-1}), volume (C_{vol}) and basal area of the chamber (S in cm^2) and the initial rate of change in CO_2 mole fraction (dC/dt). The automated system was set within the experimental vineyard (row and inter-row areas) 72 hours before the first measurement cycle. The system carried out eight measurement cycles per day at 3:00, 6:00, 9:00, 12:00, 15:00, 18:00, 21:00 and 24:00 hours. Each measurement cycle lasted 55 minutes.

EMI technique

EMI measurements were performed by means of a multi-frequency EMI sensor (GSSI Profiler EMP-400), with intercoil spacing of 1.2 m and operating simultaneously to 8, 13, 15 kHz in order to explore soil layers at increasing depth. The principle of operation is based on a transmitting coil which induces a magnetic field that varies in strength with depth in the soil. The magnetic field, strongest about 0.4 m below the soil surface, has an effective sensing depth of about 1.7 m (Allen et al., 2007). A receiving coil reads primary and secondary “induced” currents in the soil. The relationship between these primary and secondary currents measures the apparent soil conductivity. The instrument sensitivity is variable according to non-linear functions and soil depths (McNeil, 1990).

Trials

EMI measurements

The first EMI measurement was carried out before the start of the experiment (April 2009) in order to identify EC_a uniform area within the vineyard to set the static soil respiration apparatus.

Other EMI measurements (summer 2011) were performed within the experimental vineyard to evaluate the eventual relationships between EC_a signals and soil respiration rates obtained by the portable instrument (Li-Cor 6400-09).

Under our experimental conditions, data were collected continuously (every 0.75 seconds, 3960 points per hectare). Walkway speed along vineyard inter-rows was steady (around 4-5 km h^{-1}). Each single data acquisition was georeferred by GPS. The output used was EC_a measured in millisiemens per meter (mS m^{-1}). 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 metal trainers in the vineyard were not taken into account in the elaboration phase.

Evaluation of the reliability of the prototype for TSR measurements

In order to assess the reliability of our prototype for TSR measures, a test was carried out before the start of the experimentation to compare our soil respiration data with those obtained by means of Li-Cor 6400-09 equipped with soil chamber, an apparatus widely used by the international scientific community. For testing, four soil chambers were installed and connected to the prototype.

The comparison was performed in the same experimental vineyard for five days within two months. During the comparison, the prototype system was normally programmed to perform eight cycles of measurements per day (one cycle each three hours). The measurements by Li-Cor 6400-09 were done at different times during the day, but always after the chamber re-opening, by placing the Li-Cor chamber on the soil within our system's chamber and performing five consecutive measurements (replicates). Fifty-two cycles of measurements were performed during the comparison test. Finally, data acquired with the two different systems and expressed as g CO_2 m^{-2} h^{-1} were compared by Pearson's correlation.

Long term measurements of TSR by the multi-chamber automatic system

On 14 May 2009, eight soil chambers were installed on the soil surface at different distances from the row (4 chambers around the vine trunk, and 4 chambers in the inter-row area defined from now on as row and inter-row positions, respectively) (Figure 1) within the uniform area previously identified by the EMI campaign. Herbaceous plants growing in the chambers were cut off weekly at ground level and litter in the collars removed.
TSR data, expressed as g CO_2 m^{-2} h^{-1}, were recorded from May 2009 to October 2011.
A total of 340 days of measurements were performed during the experimental period. TSR values of each soil chamber respiration were acquired and processed using a specific spreadsheet (Microsoft Office Excel 2010) with which the data quality control was performed. Anomalous measurement cycles, which happened accidently during the experimental period due to technical problems (battery management, mechanical breakage of chambers), were not taken into account. In addition, due to many logistical problems, there were periods of system inactivity (winter 2009-springtime 2010). A final number of 250 measurement days (corresponding to 75% of the total acquired data) were aggregated in order to obtain hourly and daily averages of TSR. To recover daily TSR missing data due to the measure lay-off for the prototype maintenance, TSR measurements at 6:00 and

15:00 were taken into account. According to Irvine and Law (2002), these data are representative of daily minimum and maximum soil respiration rate, respectively. Daily TSR data were aggregated for week (from the minimum of 2 to 7 days of complete measurements per week). Finally, in order to identify daily TSR trends, hourly data were averaged and grouped according to the different seasonal periods (from 1 April to 30 September - growing season - and from 1 October to 31 March - vine dormancy) and the diverse positions (row and inter-row).

Evaluation of TSR spatial variability

Twenty polyvinyl chloride collars of 0.105 m in diameter and 0.10 m in height were inserted in the soil at 0.08 m depth according to a regular grid within the vineyard along the inter-rows. The number of collars, established taking into account the suggestions reported in Davidson et al. (2002), gave an accurate estimate of the average value of TSR under open field conditions. The advantage of employing such a high number of collars in this research was that it provided enough data couples EC_a *versus* TSR to search for a correlation between the two variables and to build a reliable regression. Each collar position was georeferred. To reduce a disturbance-induced CO_2 efflux, collars were installed at least 48 hours prior to the measurement campaigns. The herbaceous plants in the collars were cut off and litter removed in coincidence of the collar setting. TSR values, expressed as g CO_2 m^{-2} h^{-1}, were measured on 7, 16 June and 31 July 2011 at 6:00 and 15:00 hours which are the daily moments of minimum and maximum soil respiration rate (Irvine and Law, 2002). A single cycle of concentration increase was performed in each specific collar position due to the highly reproducible values. The average distance among TSR monitoring sites was 30.5 ± 15.2 meters. This configuration (number and location of collars) in the experimental vineyard allowed the completion of CO_2 efflux sampling in minimal time (around 1 hour) and with minimal variation in soil temperature. EMI campaigns were performed after each CO_2 flux measurement. The relationships between EC_a signals and TSR were determined.

Statistical analysis

The descriptive statistical analysis was performed on climatic (potential evapotranspiration, air temperature, air relative humidity) and soil physical parameters (soil temperature, soil water content, soil chamber humidity), TSR and EC_a.

Statistical analysis was performed on TSR data in order to highlight any temporal (at weekly scales) and spatial differences (with respect to chamber positions).

The spatial variability dependence of EC_a and TSR (at field scale) was analysed by means of geostatistic techniques (Webster and Oliver, 1990) and the form of semivariogram (eq. 2) was determined using the following model (Burrough and McDonnell, 1998):

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

where ɣ(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 x_i; and $Z(x_i + h)$ is the value of variable Z at point $x_i + h$. Plotting ɣ(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 semivariance value, called sill, is represented by the symbol $C_0 + C_1$ and is approximated similar to the variance of the analyzed data. In this experiment, it was similar to the variance of EC_a and TSR data. 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 parameters C_0, $C_0 + C_1$, and α are currently used in semivariogram fitting equations to compare the spatial variability models of TSR and EC_a. The ratio between nugget effect and sill ($C_0/(C_0 + C_1)$), expressed as a percentage, 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 $(C_0/(C_0 + C_1)) \leq 0.25$, $0.25 < (C_0/(C_0 + C_1)) < 0.75$, and $(C_0/(C_0 + C_1)) \geq 0.75$, respectively. Finally, according to Cambardella et al. (1994) for EC_a and TSR data, the degree of spatial dependence of the parameter (DSD) and the root-mean-square error (RMSE) were determined.

The least square procedure, using VESPER Software® 1.6, showed that the stable semivariogram was the better model. 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 values and TSR, linear regressions were calculated using EC_a data relative to the specific collar positions. Statistical regression analyses, showing a minimization of the sum of square residuals, a normal distribution of the data residues, and the highest statistical significant relationship, were selected.

The strongest relationship found was used to estimate TSR data at field scale. The equation (eq. 3) was the following:

$$TSR_{estimate} = EC_{a\text{-}measured} \cdot a + b \qquad \text{eq. [3]}$$

where a and b represented the slope and the intercept, respectively.

Daily mean values of EC_a were used to create a map of spazialized TSR at the field scale by means of the kriging method. The statistical analysis was performed using STATISTICA® 6.0 (Stat-Soft, Inc.; www.statsoft.com).

Results

Comparison test between soil respiration apparatus

During the 52 measurement cycles, CO_2 rate measured by means of Li-Cor 6400-09 ranged from 0.19 to 2.11 g CO_2 m^{-2} h^{-1} while the prototype system recorded values from 0.36 to 1.79 g CO_2 m^{-2} h^{-1}. Soil temperature fluctuated from 14.5 to 30.1°C while soil moisture ranged from 5.0 and 26.7 % (v v^{-1}). Sensors of Li-Cor soil chamber measured humidity values (% air) from 26.3 to 84.5 % and IRGA air humidity from 31.3 to 75.2 %.

A strong correlation was observed by interpolating TSR values recorded by the two apparatus compared. The two systems showed a significant agreement at each measurement ($r = 0.93$, Figure 2). On average, the prototype overestimated the efflux by about 13% with respect to Li-Cor 6400-09.

Temporal dynamic of TSR

Long term measurements of TSR allowed to verify the temporal dynamics of CO_2 output from soil. The integration of hourly values allowed us to determine the daily mean of TSR. Afterwards, daily values of TSR were aggregated to determine the weekly means of TSR.

In Figure 3, the weekly dynamic of TSR (mean 2009-2011) according to the chamber positions (row and inter-row) was reported. Total soil CO_2 rates showed a high variability and ranged from 0.8 - 43.7 g CO_2 m^{-2} d^{-1}. Location means were equal to 16.6 ± 11.6 and 10.8 ± 7.8 g CO_2 m^{-2} d^{-1} (mean ± standard deviation) in row and inter-row positions, respectively.

Statistical differences of TSR were recorded between row and inter-row positions in specific temporal periods (especially in summer and autumn) (Figure 3). On average, TSR measured in the row position was approximately 35% higher than that recorded in the inter-row positions. TSR showed an increase from springtime to the beginning of the summer. In springtime and early summer of each year, the soil CO_2 efflux reached the highest rate (Figure 3). After these periods, a reduction of TSR, equal to 45-50% compared to previous weeks, was recorded (from 38.3 to about 17.2 g CO_2 m^{-2} d^{-1} in 2009 and from 30.5 to 14.2 g CO_2 m^{-2} d^{-1} in 2010); then, in the first autumn months, TSR values showed an increase (up to 22.4, 20.3 and 15.5 g CO_2 m^{-2} d^{-1}, respectively in 2009, 2010 and 2011). In the last quarter of 2009 and 2010, a significant decrease of TSR (up to 5.1 and 4.8 g CO_2 m^{-2} d^{-1}, respectively) was observed.

The average seasonal trends of TSR, determined as a result of long term measurements, are shown in Figure 4. A peak of soil respiration occurred at 15:00 hours in all seasons of the year and for each position (row and inter-row). The TSR daily minimum point occurred for any position in the early hours of the morning.

There was a clear difference between the periods considered (Figure 4). During the growing season (from April 1 to September 30), TSR mean values were always greater than 0.5 g CO_2 m^{-2} h^{-1}. In particular, the contribution to the total value of TSR by roots and by the largest community of microorganisms was evident in the row position. The portion of soil located in inter-row position, remained at average lower values of 30-35% compared to TSR values measured in the row.

During the dormancy period (from 1 October to 30 March), TSR average values varied between 0.22 and 0.40 g CO_2 m^{-2} h^{-1}. The difference in TSR values between the two positions were reduced to the minimum (15%).

By comparing the same position over time, TSR measured on the row was reduced by an average of 0.45 g CO_2 m^{-2} h^{-1} passing from the growing season to the winter break. TSR measured in the inter-row position showed on average a smaller reduction varying from 0.56 g CO_2 m^{-2} h^{-1} of the growing season to 0.30 g CO_2 m^{-2} h^{-1} of the dormancy period.

During the first experimental year (2009), the effect of the single supplemental irrigation (33 mm) performed in August was evaluated. Climate parameters acquired by the Regional Service station and soil parameters measured in the field from 30 July to 5 August and from 7 to 13 August were reported in Table 3. In particular, soil water content significantly increased from one week to the other reaching values close to soil field capacity especially in the area under the drippers (row positions) (Table 3). Details on TSR dynamic (daily means) measured before and after irrigation were depicted in Figure 5. The week after the supplemental irrigation, CO_2 soil efflux showed on average a significant ($P < 0.001$) increase equal to 300%. Furthermore, significant differences were found between the examined positions (row and inter-row) (Figure 5).

Finally, the daily integration of hourly values of TSR was correlated with the daily mean of TSR measured at 06:00 and 15:00 (Irvine and Law, 2002). A significant relation among mean CO_2 effluxes was found ($R^2 = 0.95$ at $P < 0.001$).

Spatial variability of TSR

Total soil respiration, measured during summer 2011, allowed the verification of the spatial variability of CO_2 fluxes from the soil vineyard. Effluxes measured with Li-Cor 6400-09 at 06:00 and 15:00 ranged from 0.09 to 0.59 g CO_2 m^{-2} h^{-1}. No difference was found among the daily averages of the measurement days (Table 4). The geostatistical analysis performed on data taken on 31 July 2011 showed that the spatial dependence of TSR was included within 25 meters (TSR mean, Relative standard deviation-RSD, C_0, C_1, α, DSD and RMSE were 0.35 g CO_2 m^{-2} h^{-1}, 0.04, 0.02, 0.03, 24.82, 0.06 and 0.02, respectively).

Daily EC_a values, as the result of EMI campaigns performed after each CO_2 fluxes measurement, did not show statistical differences (Table 4).

EC_a values showed similar distribution among the frequencies used and a wide spatial variability (Figure 6). In particular, EC_a decreased with soil depths (8 kHz) and showed evident areas at different conductivity (e.g. in the North of the vineyard a low conductive area, in the center a more conductive area). Also for EC_a values, the geostatistical analysis carried out on data taken on 31 July 2011 showed a EC_a (13 kHz) spatial dependence included within about 22 meters (EC_a mean, RSD, C_0, C_1, α, DSD and RMSE were 31.56 mS m^{-1}, 0.16, 0.31, 12.47, 22.01, 0.02 and 0.29, respectively).

Significant relationships were found by interpolating TSR values and EMI signals (daily means) corrected for soil temperature (Corwin and Lesch, 2005). In particular, inverse relationships were found evidencing a decrease of EC_a values linked to an increase of CO_2 rates (Figure 7). Pearson's correlation (*r*) ranged from -0.40 to -0.83.

The spatialization of the soil respiration rates at field scale was performed for each measurement day (7, 16 June and 31 July 2011) using the linear regression ($TSR = EC_a$ x -

0.01 + 0.85) between TSR values and EMI signal ($R^2 = 0.69$). The map of TSR derived, reported as an example in Figure 8, showed a wide spatial variability of the estimated parameter within the experimental vineyard.

Discussion

Instrument calibration

CO_2 fluxes measured by means of the prototype system were overestimated at m^2 scale when compared to data obtained with Li-Cor 6400-09 (Figure 2). The difference between the two systems can be attributable to the size of the chambers which consider a different soil area (soil spatial microvariability). Also Healy et al. (1996) and Pumpanen et al. (2004), by comparing different TSR measurement systems, reported a minimal underestimation of the CO_2 fluxes measured by the Li-Cor 6400-09. According to these authors, this could be due to an altered diffusion gradient which slows the CO_2 diffusion from soil when the chamber is placed on the soil surface. In any case, a systematic correction of data taken by the prototype was able to be performed.

Temporal variability of TSR

The variability of TSR (Figure 3) was affected by the climatic parameters which in turn influenced soil microbial communities and root activity (Lardo, 2012).

Rates of CO_2 efflux varied over the day in response to changes in soil temperature and soil moisture. Weekly changes in TSR measured in this study (Figure 3) have been observed elsewhere and have attributed to root growth, phenology and activity (Zhang et al., 2013), availability of organic carbon substrates for microorganisms (Wang et al., 2003; Khomik et al., 2006; Buysse et al., 2013) and seasonal climatic conditions (Zhang et al., 2013). The high levels of TSR recorded in the first and second growing seasons could be due also to the compost amendment that provided the organic substrate to the microorganism communities (Figure 3). Other abiotic characteristics such as solar radiation, evapotranspiration and wind speed also affected TSR (data not shown) confirming their relationships with TSR as found by other authors (Raich et al., 2002; Reichstein and Law, 2003; Takle et al., 2004; Hibbard et al., 2005).

Under our experimental conditions, roots of vines and spontaneous crop gave their contribution to TSR (Figure 4). This phenomenon was evident especially during vine growing seasons (Figure 4) and it was supported by the higher root density and total bacterial biomass found in the row position than in the inter-row which was affected by the continual trampling of agricultural machinery for tillage and for pest and disease control (Lardo, 2012).

The influence of water stress on root respiration is mentioned by many authors (Bahn et al., 2006; Carlisle et al., 2006; Xiao et al., 2007). Our results showed an important effect of soil water content especially when water became a limiting factor (summer months) (Table 3, Figure 5). In particular, our work focused on the effect of irrigation treatment on TSR at constant climatic parameters (Table 3). A sharp increase of TSR rates - up to fourfold (Figure 5) - was observed especially along the row position where the irrigation water was distributed by drippers. These findings are in accordance with those of other authors who reported that soil water availability had a strong influence on TSR rate in different agroforestry systems (Saiz et al., 2006; Jabro et al., 2008; Grünzweig et al., 2009).

Finally, a strong relationship among the daily values of TSR coming from the integration of hourly data and the daily mean of TSR measured at 06:00 and 15:00 was found ($P < 0.001$; $n=290$) as suggested by Irvine and Law (2002). These authors found that measurements of daily minimum and maximum fluxes overestimated the mean daily flux by 7%. Similarly, an overestimation of around 8% was found under our experimental conditions (290 pairs in comparison).

Spatial variability of TSR and EMI signal

The significance of within-field spatial variability of soil properties has been scientifically acknowledged and documented (Doolittle et al., 2001; Corwin et al., 2003; Davies 2004; Morari et al., 2009; Tromp-van Meerveld and McDonnell, 2009). In our experimental case, TSR showed a wide variability within the vineyard (Table 4) being an integrated variable of soil chemical-physical and biological parameters.

To our knowledge, there are no published studies on the spatial variability of soil CO_2 effluxes at the scale of entire vineyard. Moreover, it is difficult to compare the spatial variability of soil CO_2 effluxes among different studies, because of differences in the size of the experimental plots and the number of sampling points (Fang et al., 1998).

EC_a values rose as the wavelengths used decreased and soil depth exploration increased (Figure 6). The EC_a spatial distribution was very similar for all the frequencies used (Figure 6). The EC_a values did not change among the measurement days. Such evidence could be due to the similar pedo-climatic conditions occurred in the different measurement days. The geostatistical analysis, performed on TSR and EC_a data acquired within the experimental vineyard, showed a spatial dependence over a distance of 22-25 meters. Such a finding ascertained the choice of the sampling grid (average distance among collars equal to 50 meters) and allowed the proper assessment of the variables studied at the field scale.

Perspectives for the EMI signal use

A significant relationship between TSR values and EMI signals was found (Figure 7). Allaire et al. (2012) considered EC_a as a simple physical property of soil. With recent investigations, a revised view was provided by attributing an important role at EMI signal due to its integration with all soil features included in the soil biological activity (Valckx et al. 2009; Joschko et al., 2010; Lardo et al., 2012).

The inverse relationships found between TSR and EC_a allowed us to create a map of spatial variability of TSR (Figure 8). The EMI technique could therefore be an effective tool to study the spatial variability of this integrated variable, by reducing the amount of expensive measurements that are usually needed for an environmental characterization. This integrated process could reduce the number of soil samplings and their cost and return a map of the distribution of soil parameters or indicators at field level.

Conclusions

In this study the spatial and temporal variability of TSR during three growing seasons was assessed in a vineyard managed with sustainable techniques.

At field scale, our TSR data were accurate due to the length of the observation period and the measurement frequency. These characteristics were able to highlight TSR changes at different temporal scales (from daily to seasonal).

A strong correlation between TSR and soil EC_a was found confirming EMI technique as a useful tool to evaluate spatial variability of soil parameters. This finding allowed us to spatialize punctual TSR data at field scale. TSR spatialization gave a more detailed view of CO_2 emissions distribution within the vineyard. EMI technique could be a useful tool to compute accurately the global CO_2 emissions which are a complex and hard to measure component of the agrosystem carbon balance.

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