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CO_2 and H_2O fluxes due to green manuring under Mediterranean conditions

Rossana Monica Ferrara, Nicola Martinelli, Gianfranco Rana*

CREA, Research Centre for Agriculture and Environment
*Corresponding author. E-mail: gianfranco.rana@crea.gov.it

Abstract. Green manure (GM) is supported by agronomical protocols for improving soil fertility and sustainability of agriculture. The environmental and agronomical efficiency of GM can be evaluated in terms of carbon dioxide (CO_2) and water (H_2O) fluxes. These fluxes were monitored by eddy covariance method, together with meteorological data, before and after faba bean (*Vicia faba* spp. minor L.) GM performed in a semi-arid Mediterranean region. The addition of fresh biomass into the soil increases the microbial activity with a positive priming effect: the addition of ready decomposable carbon to the soil increased CO_2 respiration and surface evaporation. The measured C emitted under CO_2 form during the whole experimental period corresponded to 78% of the C incorporated, while evaporated H_2O in the same period represented 72% of water supplied by encapsulated biomass and precipitations. The cumulated loss of C after GM until the soil preparation of the successive crop was 2957 kgC ha^{-1}, in the same period 200 mmH_2O were lost by soil evaporation.

Keywords. Faba bean (*Vicia faba spp. minor L.*), semi-arid, eddy covariance, surface temperature, aridity index.

1. INTRODUCTION

The green manure (GM) by using a short-season legume crop is a suitable agro-technique because improves soil organic carbon content (C), sustains productivity and represents an important ecosystem service mainly related to the soil nitrogen (N) recycling (Yadav et al., 2000; Tosti and Guiducci, 2010; Couëdel et al., 2018). The practice is suggested by national and international agronomical protocols, such as the developing plan of rural areas of Italian regions (PSR 2014-2020, Measure 10.1.2) which supports the introduction of faba bean or field peas between two cereal crops, and the European EC Regulation No 834/2007 which imposes GM in organic production (EC, 2007). The ploughing of legume cover crops is usually performed between the flowering and the early pod stages, leaving biomass on the surface or/and incorporating it, whole or chopped, into the soil, ensuring N and C gains for the development of the subsequent crop (i.a. Alluvione et al., 2010). Furthermore, GM increases soil fertility and quality (Zhang and Fang, 2007) and stimulates microbial growth and activity and nutrient mineralization (Eriksen and Gross, 2005). In particular, faba bean (*Vicia faba L.*)

can provide up to 270 kg fixed N ha^{-1} (Köpke and Nemecek, 2010), including a contribution of 100 kgN ha^{-1} from the below-ground biomass (Rochester et al., 1998). However, the application of residues with low C:N such as the legume crops increases the rate of biomass decomposition (De Neve and Hofman, 1996), increasing carbon dioxide (CO_2) fluxes (Huang, et al., 2004). Muhammad et al. (2019), by a meta-analysis, showed that residues placed at soil surface will reduce CO_2 emissions compared to their incorporated due to a decreasing in the rate of decomposition. The ending of CO_2 losses due to GM is uncertain: the CO_2 emission process can exhausted in a few days (Alluvione et al., 2010; Heller et al. 2010; Shaaban et al., 2016), in one month (Mancinelli et al., 2013) or it can last until several months (Curtin et al., 2000). Surely, when GM implies crop incorporation into the soil, the starting of CO_2 emissions after GM are due to the tillage operation which causes the sudden physical release of CO_2 entrapped in soil pores from previous microbial activity (Reicosky et al., 1997). The duration of this *degassing*, as defined by Rochette and Angers (Rochette et al., 1999), can be of few hours, depending on soil microclimatic conditions during the time of the year when the tillage is performed (Álvaro-Fuentes et al., 2007; Rochette et al., 1999). Moreover, the CO_2 emissions can be explained by the increased soil organic matter (SOM) decomposition due to the addition to the soil of fresh biomass containing ready decomposable C (Kuzyakov and Domanski, 2000). However, literature reports different outcomes when comparing CO_2 fluxes from bare and GM amended soil, with cases of no differences (Liebig et al., 2010) and others showing an increasing of CO_2 losses by GM (Kallenbach et al., 2010). These differences can be explained taking into account the plant species and critical high emission moments after cover crop residues addition to the soil (Bodner et al., 2018). Mancinelli et al. (2013) demonstrated that when the green matter is incorporated into the soil, the combined effect of temperature and precipitation, given in terms of aridity index, could cause a priming effect of SOM, also promoting soil mineralization processes and increasing CO_2 fluxes.

Finally, considering the impact of water and temperature on soil CO_2 dynamics, it is necessary to evaluate CO_2 fluxes either before or after GM, as well as to study their relationships with H_2O fluxes and temperature regime, in order to understand the effects of GM on the environment in any climatic region (Skinner et al., 2019). The continuous monitoring of CO_2 and H_2O fluxes at hourly scale, together with meteorological variables, immediately before and after GM, gives the chance to identify relationships among CO_2 emissions by GM and the climatic conditions.

The main aim of this study was to verify that GM increased soil CO_2 emissions due to (i) tillage and (ii) input of organic residues, evaluating the climatic effects on these two sources of CO_2 emissions.

2. MATERIALS AND METHODS

2.1 The site and the crop

The trial was carried out on a 2.5 ha field located within the CREA-AA experimental farm sited in southern Italy (Rutigliano-Bari, 41° 01' N, 17° 01' E, altitude 147 m a.s.l). Faba bean (*Vicia faba spp. minor L.*) was sowed on 19^{th} February 2014 and GM was carried out on 22 May 2014, incorporating crop into the soil at 20 cm depth. Following the usual practice of the area, it could be estimated by eye that almost 70% of the aerial green part of the crop was incorporated into the soil.

The soil was classified as fine, mixed, super-active, thermic Typic Haploxeralfs, clay-loam. Total N and total organic carbon content (TOC) at two depths (0–20 cm and 20–40 cm) were evaluated with mean values equal to 0.92 ± 0.06 gN kg^{-1} and 10.3± 0.12 gC kg^{-1}, respectively.

The climate at the site is classified as semi-arid Mediterranean, with mild winters and warm-dry summers; the mean annual temperature was of 15.7 °C and the mean annual precipitation was of 535 mm $year^{-1}$ (Campi et al., 2009), mainly concentrated between the autumn and the late winter. The mean annual water deficit (reference evapotranspiration, ET_0 less rain) was 560 mm.

Fresh and dry weight of above and below-ground biomass, together with plant height and double-sided green leaf area (LAI Licor® 300, USA) were measured according to a randomized sampling design. Mean LAI was equal to 6.2 ± 2.2 m^2 m^{-2} and mean height was equal to 81.8 ± 16.6 cm. Above-ground C and N were quantified by TOC Vario Select analyser (Elementar, Germany) and the Kjeldahl method, respectively: the above-ground C and N were 42.2% and 2.7% on a dry weight basis, respectively. The below-ground C and N were equal to 43.2% and 1.6%, respectively. On the basis of the above reported data, the above-ground biomass provided to soil a total estimated supply of 208 kgN ha^{-1}, 3230 kgC ha^{-1} and 4.6 mmH_2O. The below-ground plant parts contributed with an amount of 22 kgN ha^{-1}, 590 kgC ha^{-1} and 1.5 mmH_2O, respectively. The C:N ratio was equal to 15.5 and 27.3 for the aboveground and the belowground biomasses, respectively.

2.2 CO_2 and H_2O fluxes

CO_2 and H_2O fluxes were measured by eddy covariance (EC) method, a micrometeorological technique based on the covariance between the instantaneous vertical wind speed (w) and the concentration of the scalar (Lee et al., 2004).

The EC CO_2 and H_2O fluxes were measured in 2014 from March 7th until September 17th: see Rana et al. (2018) for all details about the trial and eddy covariance data analysis carried out by EddyPro® software (http://www.licor.com/eddypro). In this study the period from May 15th (one week before GM) until September 17th (last day before new soil managements for the following crop) was analysed.

The EC tower were equipped with a three-dimensional sonic anemometer (USA-1, Metek GmbH, Germany) for measuring wind components and sonic temperature, and a fast-responding open-path infrared gas analyser LI-7500 (IRGA, LI-7500, Li-COR Inc., Lincoln NE, USA) for detecting atmospheric CO_2 and H_2O concentrations. These sensors were placed at the centre of the plot at 1.2 m above the top of the canopy, adjusted to follow its growth for the entire growing season, while, after GM, the measurement height was at 1.10 m above soil surface. Data were sampled at 10 Hz by an Industrial Computer (Advantech, USA) running a resident software (MeteoFlux, Servizi Territorio, S.n.c., Cinisello Balsamo, Italy) and recorded at hourly time step.

The Mauder and Foken (2004) and Kormann and Meixner (2001) approaches were followed for performing quality check and footprint analysis, respectively.

2.3 Ancillary measurements and aridity index

Air temperature (T_{air}), relative humidity, precipitation and incident global radiation (R_g) were continuously measured at hourly time step by standard sensors placed on a grass meadow close to the experimental field. The soil-crop surface temperature T_{surf} was measured by four infrared radiometers (IRR-P, Apogee Instruments Inc., Utah, USA) at the centre of the plot, close to the EC tower, positioned 1 m above the crop, at an angle of 60° on the horizontal and pointing toward each of the four cardinal points. Data were collected until 1st July by a CR10X (Campbell Scientific Inc., USA) at a frequency of 0.1 Hz and stored for as hourly averages; on 2nd July a serious failure interrupted the acquisition of T_{surf} values.

The aridity index, AI, firstly introduced by De Martonne (1926) and widely used to link climatic characteristics and agricultural features (see for example Francaviglia et al., 2017; Emadolin and Reinsch, 2018), was calculated at monthly scale as:

$$AI = \frac{P_i}{T_i + 10}$$

where P_i = monthly precipitation, T_i = monthly mean air temperature. Following Mancinelli et al. (2013), the aridity index can be used to assess temporary variations of crop water conditions during crop growing season and can be related to CO_2 flux to verify the relationships between climatic factors and soil respiration.

3. RESULTS AND DISCUSSION

3.1 Meteorological conditions

The weather conditions recorded during the experimental period (T_{air}, R_g, vapour pressure deficit VPD, rain) are reported in Table 1 at monthly scale. In the whole period T_{air}, VPD and R_g followed the typical seasonal patterns for this Mediterranean area, with low values of VPD and R_g recorded during rainy and cloudy days. The precipitation throughout the experimental trial was negligible in the first days after crop incorporation until 14 June, when a huge precipitation event (30.6 mm) occurred; June and July were particularly rainy for this area (see Tab. 1) with precipitations concentrated in few stormy events.

T_{surf} followed T_{air} pattern even if about 10 °C above it during the hottest hours of the day and with similar values during the night-(data not shown).

Tab. 1. Weather variables at monthly scale: air temperature (T_{air}), global radiation (R_g), vapour pressure deficit (VPD), rain: all values are mean, except rain, which is expressed as sum.

Month	T_{air} (°C)	R_g ($MJm^{-2}d^{-1}$)	VPD (kPa)	Rain (mm)
May	17.2	20.4	1.4	17.1
June	21.3	24.4	1.8	108.1
July	22.8	21.7	1.8	107.5
August	24.1	21.3	2.0	8.5
September	20.2	15.1	0.8	30.8

Tab. 2. Footprint dimensions during daytime and night-time, calculated with the Kormann and Meixner (2001) footprint approach. Length is the length of the footprint, width is the width of the ellipse at the centre of length.

	Daytime		Night time	
	Length (m)	Half width (m)	Length (m)	Half width (m)
Mean	75.22	9.89	109.99	13.38
Max	203.84	24.40	547.53	53.85

3.2 Footprint analysis

The analysis of the source area is summarised in Tab. 2. The mean peak emitting point of the flux footprint was estimated to be around 12 m away from the mast, while on average 90% contribution to total fluxes during the daytime was provided by an area extending 134.4 m upwind.

3.3 CO_2 and H_2O fluxes

On the experimental period (15 May - 17 September) 56, 32, and 12 % of data were flagged 0 (best quality fluxes), 1 (fluxes suitable for general analysis) and 2 (discarded fluxes), respectively (Kormann and Meixner, 2001).

Fig. 1 shows CO_2 and H_2O fluxes at hourly scale from one week before GM until the end of the monitoring period. Before GM, daily trends of CO_2 fluxes followed the typical pattern of an active green crop with negative daytime photosynthesis values and night-time positive ecosystem respiration values. In the days following the GM, the CO_2 fluxes became positive during daytime, following a typical bell shape pattern; in particular, only soil respiration was detected until the soil remained bare. During the first 6 days immediately after GM the increasing observed in CO_2 emissions was due to the effect of tillage performed for incorporating the faba bean, after that the pattern of CO_2 flux was gently decreasing until the end of the considered period of measurements. During the last three days of monitoring, the CO_2 fluxes showed the pattern of an active green crop since the emerging of weeds started. It is also clear that the CO_2 emissions increased after any effective rain event, mainly due to the restart of decomposition of encapsulated biomass of remaining residue (Muhammad et al., 2019; Curtin et al., 2000), this behaviour was also observed in other studies (Álvaro-Fuentes et al., 2007), and can be explained by the physical release of the CO_2 entrapped in soil pores due to water filling and by the subsequent stimulation of soil microbial activity.

To further investigate the effect of ploughing on CO_2 emissions a zoom on the period immediately before and after GM until the first effective rain (13 June) is reported in Fig. 2, where the components of ecosystem respiration were obtained by the partitioning method applied to the eddy covariance data (Rana et al., 2018). In particular, considering the short-term effect of tillage, few days after GM, CO_2 emission was the result of the above-mentioned *degassing* and the stimulated soil microbial activity by the addition of fresh biomass. The soil respiration increased from 1.76 μmolm^{-2}s^{-1} (mean over the week before tillage) to 5.46 μmolm^{-2}s^{-1} (mean over 6 days after GM).

In order to take into account the effect of water on CO_2 fluxes, hourly fluxes of H_2O were also analysed. Before the GM the water (see Fig. 1) showed the typical daily patterns and absolute values of the actual evapotranspiration of a well-watered crop under Mediterranean climate (Katerji and Rana, 2006). With the termination of the crop by the GM, the H_2O flux decreased due to plant transpiration suppression and only evaporation process occurring. This clear trend did not occur after the first rain effective event on 13th June, in fact after this day the H_2O evaporation from bare soil was addressed by the soil water content following the water supply. Other details, including the overall trends of CO_2 and H_2O fluxes for this crop along the growing season since plants' emergence, are reported

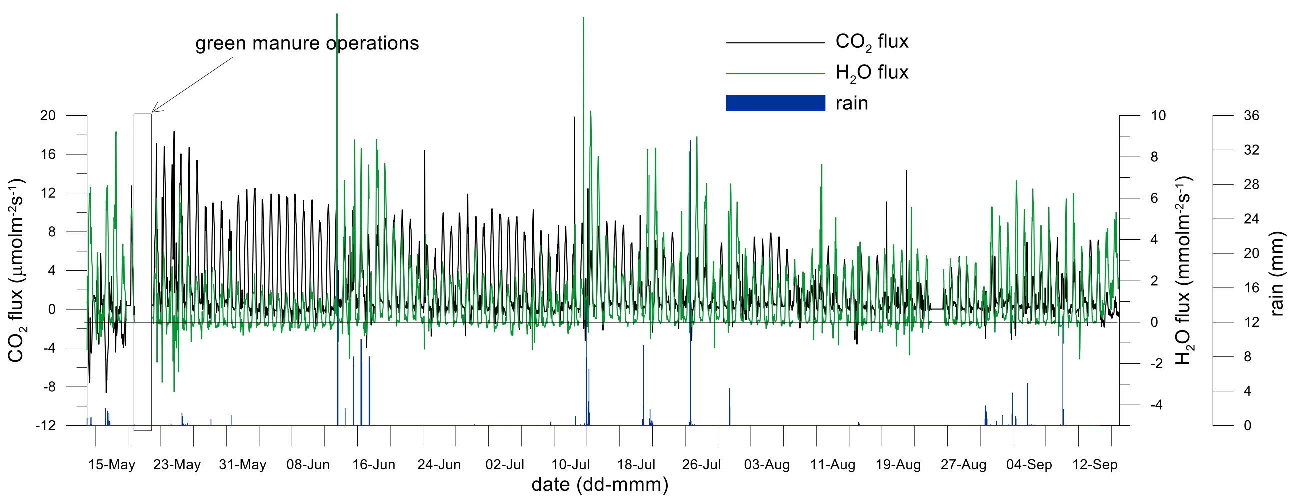

Fig. 1. Time trends of hourly CO_2 and H_2O fluxes during the trial. The rainfall and the time interval of harrowing operation for green manure are also indicated.

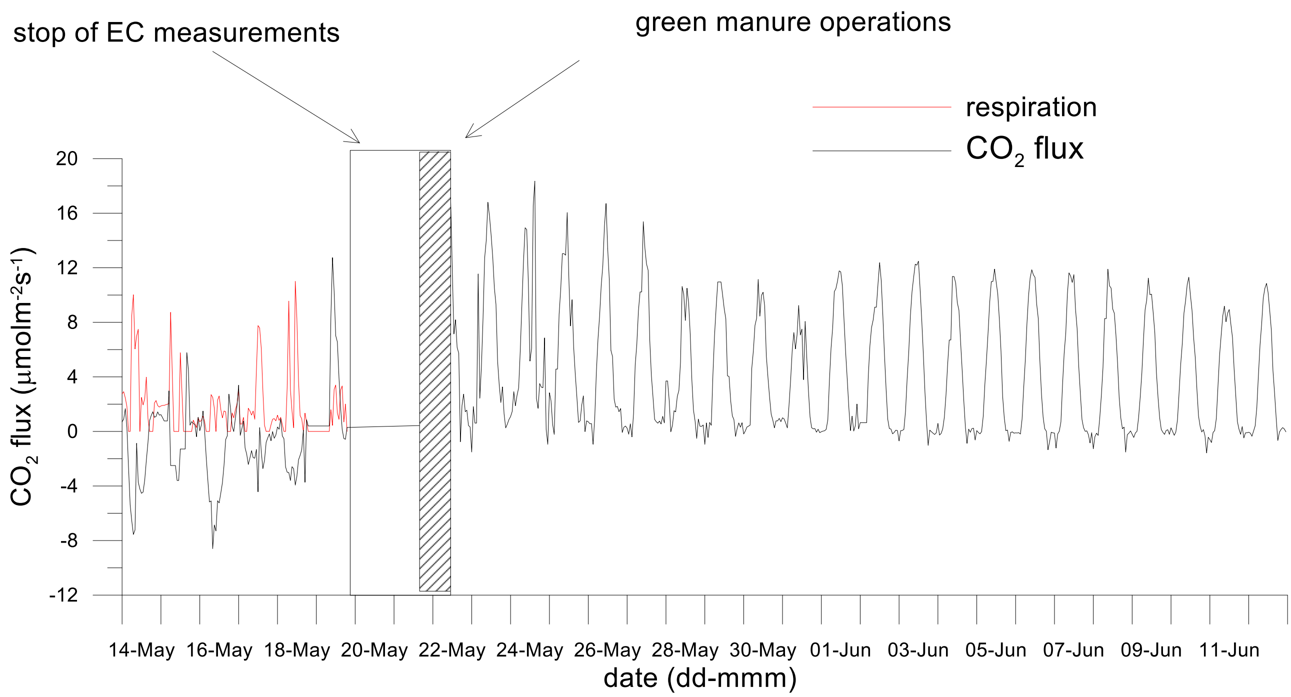

Fig. 2. Zoom of soil respiration from one week before green manure (GM) until the day of first effective rain event (13th June).

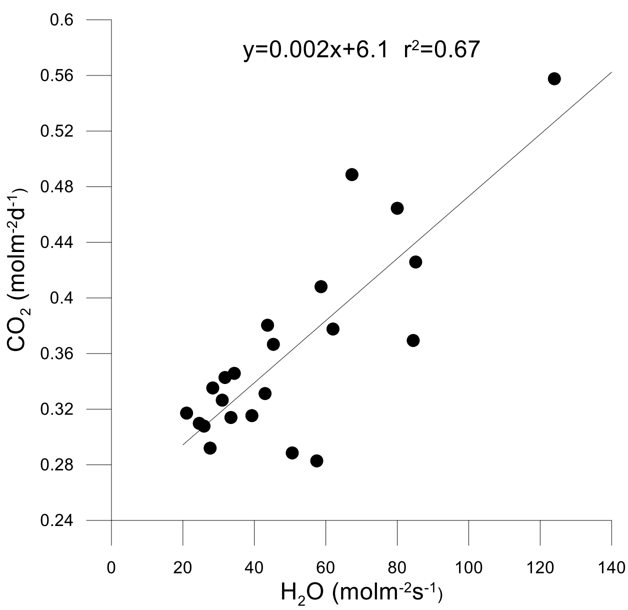

Fig. 3. Daily values of CO_2 vs H_2O fluxes in the first days after green manure until 13th June.

in Rana et al. (2018).

Since both CO_2 and H_2O fluxes decreased in absolute values starting from the first day after GM until 13th June, a possible relationship between these two variables was investigated. Actually, the comparison between total daily values of CO_2 and H_2O fluxes (Fig. 3) confirmed a correlation between them due to the analogy in the mechanisms of transport toward the atmosphere of these gases of non-stomatal origin in the absence of rain (Scanlon and Sahu, 2008).

3.4 Soil Surface Temperature effect on H_2O and CO_2 fluxes

Considering the widely demonstrated relationship between surface temperature and the soil surface evaporation (Kalma et al., 2008; Qiu and Ben-Asher, 2010), the linkage between these variables was investigated at daily scale, always taking into account the period from one week before GM until 13th June. Fig. 4 showed a clear decreasing of H_2O fluxes with the increasing of surface temperature. In particular, two periods can be distinguished: the first one before GM, when the green crop was active, and the second one; after GM, when plants were dead and encapsulated into the soil.

Then, considering that CO_2 emissions were strongly related to soil surface evaporation (see Fig. 3), which depends on surface temperature (see Fig. 4), the relationship between CO_2 emissions and the mean daily surface temperature was further investigated. The daily trend of CO_2 flux until 13th June is shown in Fig. 5: it is clear that the CO_2 flux sudden increased after GM for tillage effect. Moreover, CO_2 emissions further increased after rainy days

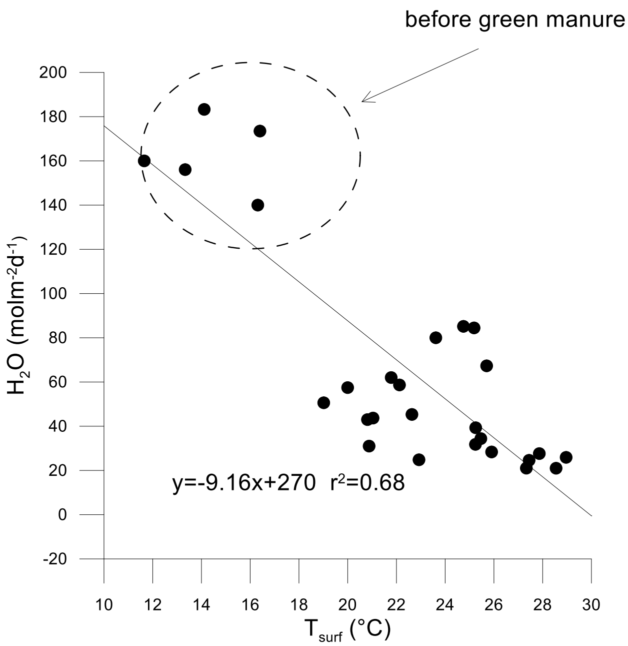

Fig. 4. Daily H_2O fluxes vs surface temperature (*Tsurf*) for the period 15 May - 13 June.

on 26th and 30th May and 1st June. One week before GM the daily CO_2 balance was still negative, and the actively growing crop performed as a CO_2 sink. Just after the GM incorporation, the soil became a net source of CO_2, reaching a maximum 2 days after the GM (24 May, around 0.5 mol m^{-2} d^{-1}) and slowly decreasing for several days until it became almost constant during the last displayed thirteen days. These results are supported by other authors: Mancinelli et al. (2013) reported analogous trends for the peaks of CO_2 emitted immediately after green manuring due to the addition of fresh biomass containing ready decomposable C, which enhances SOM decomposition (Kuzyakov and Domanski, 2000). This positive priming effect results in soil organic matter mineralization and subsequent CO_2 efflux toward atmosphere.

The relationship between CO_2 emissions as daily mean of fluxes (μmolm^{-2}s^{-1}) and T_{surf} is displayed in Fig. 6 by considering all available T_{surf} data (from May 23th until July 1st). In the first two weeks after incorporation (red symbols) CO_2 emissions were strongly related to T_{surf}, while during the last monitored weeks (white symbols) T_{surf} increasing was not related to any increasing in CO_2 emissions. This latter lack of relationship between T_{surf} and CO_2 fluxes could be explained considering that in this stage CO_2 fluxes likely came from layers of soil below the soil surface where surface temperature did not have effect. This behaviour is similarly to the results reported by Rochette et al. (2000) and Bol et al. (2003) for CO_2 emissions following slurry-C incorporation in grassland. These authors highlighted a two-stage decomposition process: (i) rapid increase in emitted CO_2 due to the decomposition of the labile and easily available fraction of C contained in the biomass, (ii) slow decrease due to decomposition of less available recalcitrant C material. In the present study, the advantage is the chance to follow at hourly scale in continuous the dynamics of these CO_2

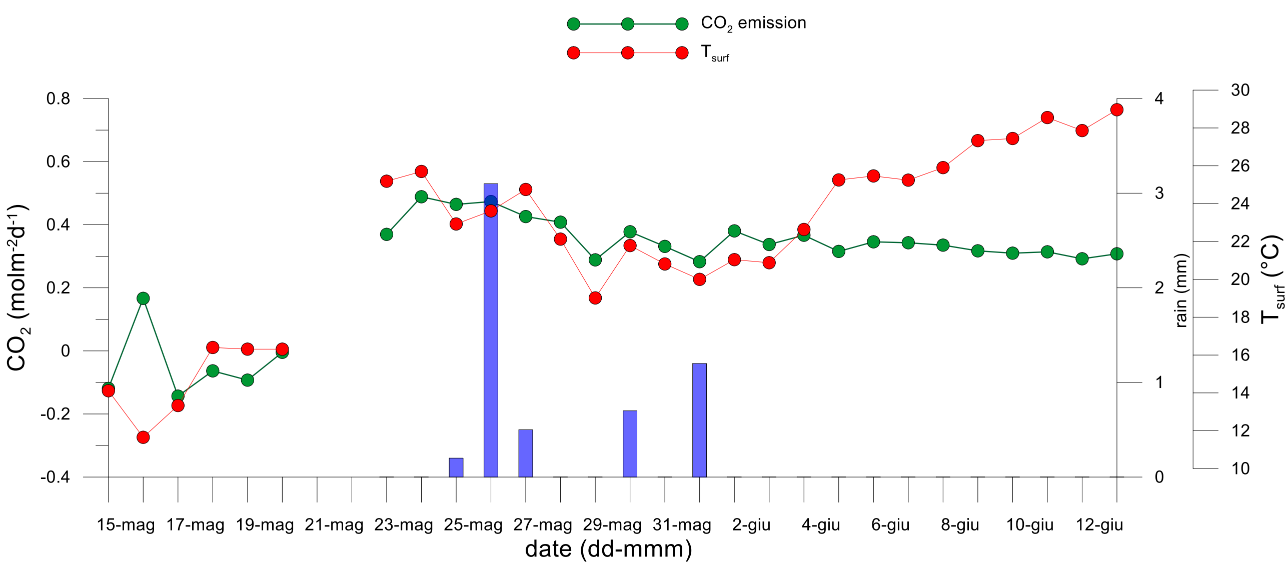

Fig. 5. Daily rain, CO_2 fluxes and surface temperature (*Tsurf*) from one week before green manure (GM) until the first effective rain (13th June).

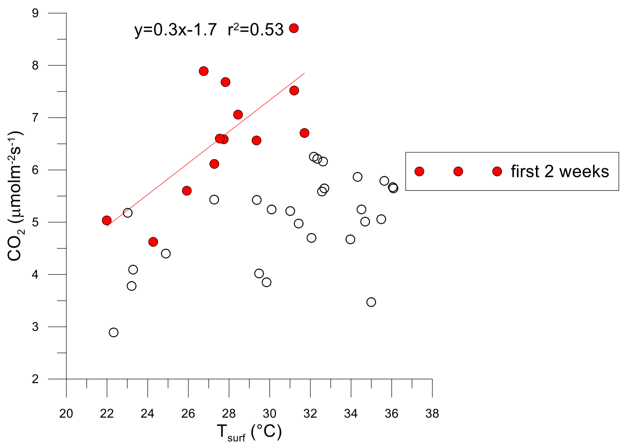

Fig. 6. Relationship between CO_2 emissions as means of hourly fluxes at daily scale and mean daily surface temperature.

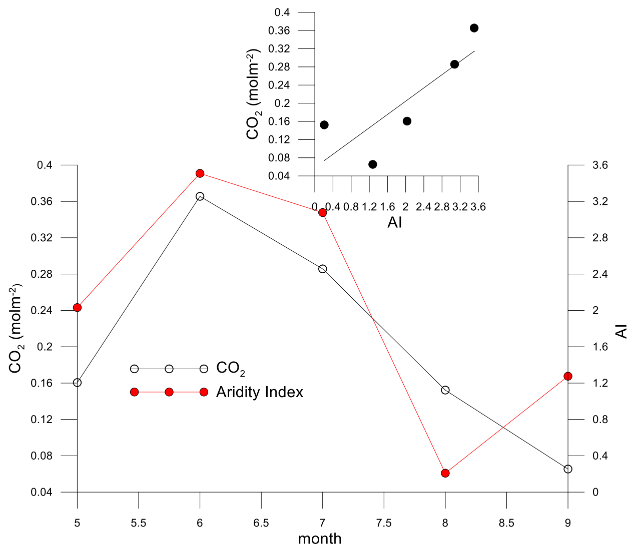

Fig. 7. Monthly patterns of Aridity Index and CO_2 flux in the experimental period; in the small upper panel the relationship between theses variable is illustrated (CO_2=0.07 AI+0.06 r^2=0.68).

releases coming from two different sources, highlighting also the effect of tillage.

The strong relationship between surface temperature and CO_2 flux during the first two weeks after GM could suggest that the majority of CO_2 production occurred in plants residue likely before it was completely dry. Parkin and Kasper (2003), in residue covered no-till field crops (corn and soybean) in Iowa (USA), and Rana et al. (2016), in a bioenergetic crop in semi-arid climate in Italy, found similar relations between CO_2 flux and soil surface temperature.

3.5 CO_2 fluxes and the Aridity Index

Fig. 7 displays the cumulated monthly soil CO_2 fluxes (in mol m^{-2}) in function of the monthly values of *AI*: the greatest values of CO_2 corresponds to the highest value of *AI*. This result is in agreement with Mancinelli et al. (2013): under Mediterranean conditions, high *AI* value at the time of green manuring may promote the start of soil mineralization processes which may result in a priming effect of native SOM. Thereafter, the decreasing in *AI* corresponds in a decreasing of CO_2 fluxes. In order to develop a finding useful for agronomical purpose, a linear relationship between CO_2 flux and *AI* at monthly scale was investigated (see small upper panel in Fig. 7), founding $CO_2=0.07\ AI + 0.06$ with high value of r^2 (0.68).

4. CONCLUSIONS

Eddy covariance measurements of CO_2 and H_2O fluxes before and after the GM of faba were performed in a typical dry environment of the Mediterranean basin. During the trial, the starting of increased soil metabolic activity and respiration due to GM was monitored in terms of increasing in CO_2 emissions, highlighting the *degassing* effect due to tillage and the emissions due to decomposition of new fresh biomass following GM: this latter CO_2 emissions was not affected by the surface temperature.

Furthermore, the addition to the soil of fresh biomass containing ready decomposable C increased CO_2 respiration and surface evaporation. The measured C emitted under CO_2 form during the whole experimental period correspond to 78% of the C incorporated, and evaporated H_2O in the same period represents 72% of water supplied by encapsulated biomass and precipitations.

The cumulated loss of C after the GM until the soil preparation of the successive crop was 2957 kgC ha^{-1}; in the same period, 200 mmH_2O were lost by soil evaporation. This value of emitted C after GM is comparable to those found by Hoyle et al. (2011) which report between 50% and 75% of the C in plant residues can be lost as CO_2 by microbes during the first year of decomposition.

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