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Research Article

Soil respiration dynamics in forage-based and cereal-based cropping systems in central Italy

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ABSTRACT: Studies that have investigated soil carbon dynamics under Mediterranean conditions are scarce and fragmented and contrasting results have often been reported. This study aimed to fill some gaps in our knowledge by: (i) determining annual dynamics of total (R_S) and heterotrophic (R_H) soil respiration; (ii) estimating annual cumulative R_S and R_H; and (iii) investigating the relationships between R_S and R_H and soil temperature and water content. The study was carried out in central Italy, for a plain and a hilly site, with the focus on two main cropping systems: an alfalfa-based forage system and a wheat-based rotation system. R_S and R_H showed different dynamics, with spatial and temporal variability across these sites. Estimated annual cumulative R_S fluxes were 8.97 and 7.43 t C ha^{-1} yr^{-1} for the plain and hilly alfalfa-based sites, respectively, and 4.67 and 5.22 t C ha^{-1} yr^{-1} for the plain and hilly wheat-based sites, respectively. The R_H components of R_S were 4.26 and 3.52 t C ha^{-1} yr^{-1} for the plain and hilly alfalfa-based sites, respectively, and 3.89 and 2.45 t C ha^{-1} yr^{-1} for the plain and hilly wheat-based sites, respectively. A model with a combination of soil temperature and soil water content explained 43 % to 49 % and 33 % to 67 % of the annual variation of R_S and R_H, respectively. These findings help to extend our knowledge of Mediterranean cropping systems, although further studies are needed to clarify the effects of management practices on the modelling of soil respiration efflux.
Keywords: Mediterranean, alfalfa, greenhouse gasses, soil carbon stock, wheat

Introduction

Loss of soil carbon (C) from agricultural practices is likely to have significant effects on atmospheric CO_2 concentrations (Smith, 2008) and land degradation (Ryan et al., 2008). Many studies have shown that conversion of permanent vegetation to croplands can lead to decreased soil C stock (Lal, 2004; Monaci et al., 2017), while conversion of cropland to permanent vegetation can increase this stock (Guo and Gifford, 2002; Smith, 2008). Management practices have key roles in soil greenhouse gas emissions (Paustian et al., 2000), as they directly affect the C dynamics of terrestrial ecosystems (Robertson et al., 2015). Uncertainties have been reported in terms of soil respiration dynamics and their interactions with soil temperature (ST) and soil water content (SWC) (e.g., Feiziene et al., 2015), and with other factors, such as the soil microbial population (Lai et al., 2012) and soil oxygenation (Ryan and Law, 2005). Moreover, studies on the impact of anthropic activities on soil respiration (R_S) are poorly documented (Maestre and Cortina, 2003; Almagro et al., 2009) and the available data mainly address ecosystems, where anthropogenic actions are not significant or frequent (e.g., Rey et al., 2002).

The Mediterranean region is considered one of the most vulnerable sites to global climate change, due to the expected prolonged drought period during summer and increasing rainfall in winter and autumn (Giannakopoulos et al., 2009). Studies that have investigated soil C dynamics under Mediterranean climate conditions are still relatively scarce (Oertel et al., 2015). The lack of information on such systems represents an important challenge for the scientific community (Munoz-Rojas et al., 2012).

This study aims to contribute to filling gaps of knowledge on the Mediterranean climate conditions, by: (i) determining annual dynamics of R_S and heterotrophic soil respiration (R_H); (ii) estimating annual cumulative R_S and R_H; and (iii) investigating the relationships between R_S, R_H and ST, SWC. Two study sites were selected in central Italy in plain and hilly areas used for two main cropping systems: an alfalfa-based forage system and a wheat-based rotation system. Both sites are hereafter referred to as 'plain alfalfa' (PA), 'plain wheat' (PW), 'hilly alfalfa' (HA) and 'hilly wheat' (HW) systems.

Materials and Methods

Study sites

The study sites were located in plain and hilly areas of the Marche region (Macerata Province, central Italy) where two main cropping systems were selected, as follows:

i) An alfalfa-based forage system, where the main crop was usually kept for 3-5 years, with interruption for 1 or 2 years when winter cereals were usually cultivated. This system uses hay meadows that are sometimes grazed during the autumn-winter period by transhumant flocks (Caballero et al., 2009).

ii) A typical cereal-based rotation system with winter cereals (e.g., wheat, barley), summer crops (e.g., mainly maize or sunflower), and alfalfa as a forage crop (Di Bene et al., 2016). All of these crops were rain fed, except for maize, which is usually irrigated in the plain sites.

In early Nov 2014, both study sites were identified in a representative area of these cropping systems:

i) In an alluvial plain area (43°22′20.2″ N, 13°35′26.9″ E; 28 m a.s.l.), for two adjoining fields of alfalfa-based (PA) and wheat-based (PW) systems.

ii) In a hilly area (43°20′40.9″ N, 13°36′19.5″ E; 120 m a.s.l.), for two adjoining fields of alfalfa-based (HA) and wheat-based (HW) systems.

The spatial distance between both study sites (i.e., from PA/PW to HA/HW) was approximately 3 km, as shown in Figure 1.

Cropping system description and field operation

For PA and HA fields, the soil was plowed to a depth of 0.3 m before planting alfalfa, in 2010 (PA) and 2011 (HA). In central Italy, alfalfa crops do not require any particular treatments, such as fertilizers or irrigation. The mowing of alfalfa was performed two or three times a year, during late spring and summer, which depended on weather climate conditions and crop production. During the observation period, from Jan to Dec 2015, alfalfa was mowed twice, once in the first week of May 2015, and second on the first day of June 2015.

For PW and HW fields, the soil was plowed to a depth of 0.3 m in the third week of July 2014. Secondary tillage was performed in the last week of Sept for PW, and about 3 weeks earlier for HW. Wheat was sown by the end of Oct 2014 for PW, and about 1 week later for HW. The first treatments performed during the monitoring period, from Jan to Dec 2015, was fertilizer application, with 180 kg N ha^{-1} for PW, and 150 kg N ha^{-1} for HW. The fertilizer was distributed in two sessions between the second week of Feb 2015 and the end of Mar 2015. The wheat crop was harvested for both PW and HW sites in the second week of July 2015. The soil was plowed again in the first week of Aug 2015 for both PW and HW.

The previous crop rotation used for these fields was determined through interviews with farmers, shown in Figure 2.

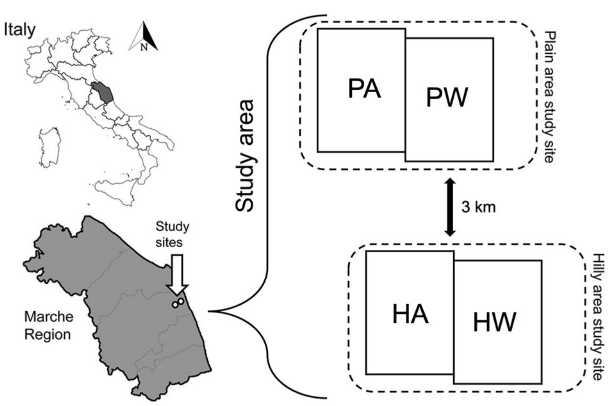

Figure 1 – Study area and study sites. PA = plain field with alfalfa; PW = plain field with wheat; HA = hilly field with alfalfa; HW = hilly field with wheat.

Study site climate

The climate of the study site is Mediterranean, and during the study period (Jan to Dec 2015), the mean annual precipitation was 908.6 mm, and the mean annual temperature was 15.9 °C. The month with most rain was Oct 2015 (190.4 mm) and with least rain was July 2015 (2.4 mm). The mean air temperatures ranged from 7.3 °C (Feb 2015) to 28.0 °C (July 2015) (Figure 3).

Study site soil

According to the United States Department of Agriculture (USDA) soil taxonomy (Soil Survey Staff, 2014), the soils of the study sites were classified as *Inceptisol*. Their basic physicochemical characteristics are shown in Table 1. Soil bulk density was determined using the cylinder method, total organic C (TOC) was determined using the Springer-Klee method, and the soil organic matter (SOM) was estimated by multiplying TOC values by the Van Bemmelen factor of 1.72 (Soil Survey Staff, 2014).

Soil respiration analysis

Soil respiration efflux was measured *in situ* using a portable, closed chamber, soil respiration system that

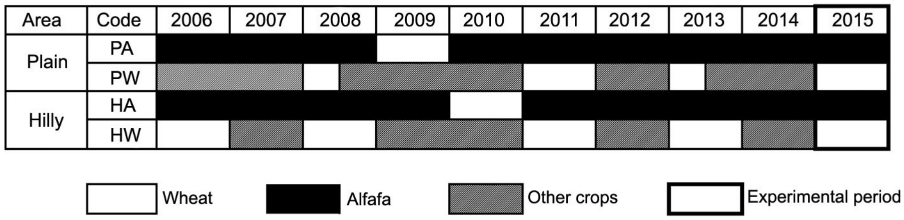

Figure 2 – Crop succession for experimental fields from 2006 to 2015, as derived from interviews with farmers. 'Other crops' include barley, pulses (e.g., pea) and vegetables (e.g., chicory). The study period was from Jan to Dec 2015. PA = plain field with alfalfa; PW = plain field with wheat; HA = hilly field with alfalfa; HW = hilly field with wheat.

Table 1 – Source and basic physicochemical characteristics of soils in different fields for both study sites. Data were obtained from the analysis of five subsamples per field collected in the first 0.3 m layer. PA = plain field with alfalfa; PW = plain field with wheat; HA = hilly field with alfalfa; HW = hilly field with wheat.

Site	Cropping system	Code	pH	Sand	Silt	Clay	Bulk density	Total organic carbon	Soil organic matter
				%			g cm^{-3}	g kg^{-1}	
Plain	Alfalfa	PA	8.08 ± 0.07	18	46	35	1.57 ± 0.06	13.60 ± 0.79	23.45 ± 0.79
	Wheat	PW	8.26 ± 0.02	24	47	29	1.64 ± 0.09	11.17 ± 0.12	19.26 ± 0.12
Hilly	Alfalfa	HA	8.25 ± 0.03	12	48	40	1.64 ± 0.06	8.13 ± 0.76	14.02 ± 0.76
	Wheat	HW	8.39 ± 0.03	8	49	43	1.46 ± 0.05	6.80 ± 0.20	11.72 ± 0.20

Data are means ± standard error (n = 5 subsamples per field).

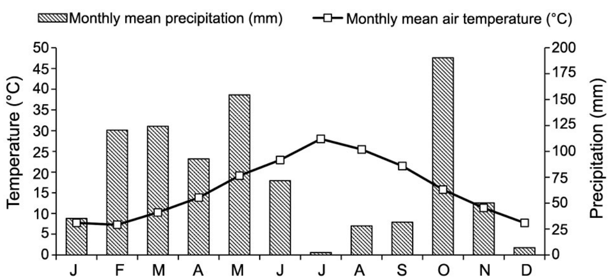

Figure 3 – Mean precipitation and air temperatures for the study area during the experimental period from Jan to Dec 2015. Data provided by the Agrometeorological Service of the Marche Region.

comprised an environmental gas monitor (EGM-4) with a soil respiration chamber (SRC-1). The measurement time was 120 s, according to Lai et al. (2012).

In early Nov 2014, a homogeneous area composed of six nonadjacent replicated subplots (3 m × 3 m) was identified for each of the four fields. For each subplot, a PVC collar (inner diameter, 0.10 m; length, 0.10 m; with perforated walls for the first 0.05 m) was inserted into the soil at a depth of 0.09 m. Three of the six subplots were used to measure R_H, removing crop roots, and using a PVC cylinder (diameter, 0.4 m; height, 0.4 m) that was open at both ends, following the method described by Alberti et al. (2010). Thus, for each field, three replicates were used to measure both R_S and R_H. R_H was measured according to Hanson et al. (2000) and the measurements are considered an indicator of the soil microbial activity.

During each CO_2 efflux measurement, the soil respiration chamber was fitted to a PVC collar. The measurements started in Jan 2015 and ended in Dec 2015, with a frequency of two to three times per month, depending on weather variability and management practices, totaling 25 measurements of CO_2 per field. Soil respiration was always measured between 08h30 and 12h00 to avoid efflux fluctuations (Xu and Qi, 2001; Almagro et al., 2009; Fan et al., 2015).

Soil temperature and water content analysis

For each plot, ST and SWC were measured simultaneously with CO_2 efflux measurements. The measurements used the built-in temperature probe of environmental gas monitor for ST at a depth of 0.10 m. SWC was determined on soil samples collected from the top 0.2 m layer, and oven dried at 105 °C for constant weight.

Data handling

The one-way analysis of variance (ANOVA) with repeated measures (PROC GLM, SAS) and least significant difference (LSD) tests for pairwise comparisons were used to test differences for R_S, R_H, ST, and SWC for each of the fields studied. To obtain the best-fit models, the regression analysis was used to examine the relationships between soil respiration (i.e., R_S, R_H), ST and SWC (Davidson et al., 1998), and a multiple regression model was adopted considering the combined effects of ST and SWC (Fan et al., 2015). The equations used are:

For R_S or R_H and ST:

$$y = a\, e^{b\,ST} \quad (1)$$

For R_S or R_H and SWC:

$$y = a + b\,SWC \quad (2)$$

For the R_S or R_H and ST-SWC combinations:

$$y = a + b\,ST + c\,SWC \quad (3)$$

where y is measured R_S or R_H (μmol CO_2 m^{-2} s^{-1}) and a, b and c are equation coefficients.

The annual cumulative R_S and R_H were calculated by linear interpolation of the CO_2 fluxes between measurement days from Jan 5, 2015, to Dec 29, 2015 (Rong et al., 2015). The one-way ANOVA was performed to test differences for cumulative R_S and R_H within the fields of the study sites (i.e., PA *vs*. PW and HA *vs*. HW).

Results

ST, SWC, R_S, and R_H showed different spatial and temporal dynamics, which varied between the study sites, fields, and dates of determination (Figures 4A-H).

Soil temperature and water content dynamics

From Jan to Dec 2015, SWC at 0.2 m of depth ranged from 11 % to 43 % for PA, from 10 % to 40 % for PW, from 10 % to 42 % for HA, and from 14 % to 41

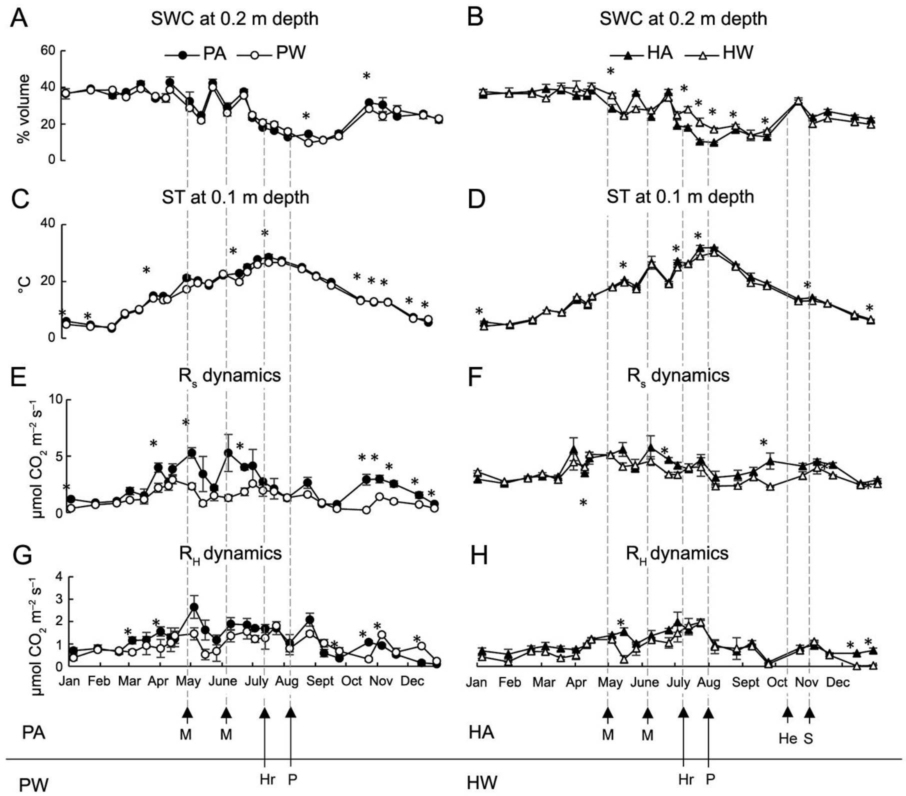

Figure 4 – Seasonal dynamics of SWC (A, B), ST (C, D), R_S (E, F) and R_H (G, H) in different fields (PA, PW, HA, HW) of both study sites (plain, hilly) during the study period from Jan to Dec 2015. Vertical dotted lines represent management practices adopted for different crops in the study fields. $^*p < 0.05$; $^{**}p < 0.01$ (LSD). Vertical bars represent standard errors. PA = plain field with alfalfa; PW = plain field with wheat; HA = hilly field with alfalfa; HW = hilly field with wheat; F = fertilizer applied; M = mowing; H_R = harvesting; P = plowing; He = herbicide; S = sowing.

% for HA. Both study sites (i.e., plain and hilly) showed very similar SWC dynamics, with the lowest values observed from July to Oct. Within this period, differences in SWC were less pronounced in the plain study sites (PA *vs*. PW) compared to the variation for the hilly study sites (HA *vs*. HW) (Figures 4A and B). The annual mean ST at 0.1 m of depth was 16.32 °C for PA, 15.63 °C for PW, 17.07 °C for HA, and 16.54 °C for HW. In both study sites, the highest ST were recorded during the summer period, which was the same period for the lowest SWC values. Differences for PA *versus* PW sites occurred mostly during winter and autumn, while for HA *versus* HW, differences were more scattered throughout the monitoring period (Figures 4C and D).

Soil respiration rates and dynamics

For the plain study site, PA and PW showed annual mean R_S of 2.48 µmol CO_2 m^{-2} s^{-1} and 1.33 µmol CO_2 m^{-2} s^{-1}, respectively. A large reduction in R_S was observed for PA in May, followed by a rapid increase from the end of May into June. This reduction in R_S occurred concomitantly to the particularly high rainfall volume in May (Figure 3). Subsequently, R_S decreased until mid-Sept. Within this observation period, R_S for PA showed two peaks to 5.3 µmol CO_2 m^{-2} s^{-1} that occurred immediately after alfalfa mowing, in the first week of May and the second week of June. R_S for PW showed an initial increasing trend until the second week of April, when it decreased to 0.8 µmol CO_2 m^{-2} s^{-1} in mid-May. Later, R_S for PW gradually increased again until July, when the grain was harvested and the plowing was performed about one month later. In the second half of April, (i.e., approximately one month after the second application of fertilizer), R_S for PW showed a peak of 2.88 µmol CO_2 m^{-2} s^{-1}. Differences in R_S were generally seen between PA and PW from the beginning of Apr to the end of June, when PA showed higher R_S than PW did. Starting from mid-Oct, R_S was again higher for PA than for PW, which lasted until the end of the monitoring period (Figure 4E).

Conversely, the hilly sites showed similar mean R_S between HA and HW (1.33 *vs*. 1.49 µmol CO_2 m^{-2} s^{-1}, respectively). The peaks in R_S were also less pronounced, but more frequent for the hilly sites, where HA showed three R_S peaks (3.85, 3.83, 4.04 µmol CO_2 m^{-2} s^{-1}) in the first fortnights of Apr, May and June. Similar to the plain sites, HA showed R_S peaks immediately after the alfalfa mowing, except for the first R_S peak at the beginning of Apr. In general, HA and HW showed increasing trends for R_S from Jan to the first day of Apr. Subsequently, two R_S decreases were recorded for HA, in Apr and May, when ST also decreased slightly. R_S for HW showed two peaks (3.35, 3.28 μmol CO_2 m^{-2} s^{-1}) for two near measurement dates in Apr, after the second application of fertilizer (Figure 4F). Overall, R_S trends were very similar for HA and HW until the first week of Aug, when differences tended to increase, which coincided with both HW plowing and ST decrease (Figure 4D). Indeed, from Jan to mid-June, R_S for HW was not different from R_S for HA, with the exception of the first half of Apr (Figure 4F).

Heterotrophic soil respiration rates and dynamics

The annual means of R_H were 1.19 μmol CO_2 m^{-2} s^{-1} for PA and 1.03 μmol CO_2 m^{-2} s^{-1} for PW. R_H for PA showed a slowly increasing trend from Jan to the first week of May, when it decreased sharply, concomitant to a sharp SWC decline (Figure 4A). After a peak of R_H of 2.65 μmol CO_2 m^{-2} s^{-1} in the first week of May, R_H remained relatively constant from June to the first half of Aug (1.68 to 1.89 μmol CO_2 m^{-2} s^{-1}). A second R_H peak for PA was seen in the second half of Aug (2.08 μmol CO_2 m^{-2} s^{-1}), which occurred together with SWC increase (Figures 4A and G). From Sept to Dec, R_H for PA remained low and relatively constant (0.11 to 1.07 μmol CO_2 m^{-2} s^{-1}). Similar dynamics for R_H for PW were relatively constant through to the beginning of May, when ST was increasing and SWC ranged between 34 % and 42 %. After plowing in the second half of Aug, differences for R_H between PA and PW were observed, from Oct to Dec. However, no differences were seen for R_H between the two plain fields (PA, PW) for the dates of the two R_H peaks for PA.

The annual means R_H for the hilly sites were 1.03 μmol CO_2 m^{-2} s^{-1} for HA and 0.80 μmol CO_2 m^{-2} s^{-1} for HW. Here, HA showed a slowly increasing R_H trend from Jan to Aug, when it then decreased to its minimum of 0.19 μmol CO_2 m^{-2} s^{-1} at the end of Sept. Very similar R_H dynamics were observed for HW, with the exception of a decrease in mid-May. Regarding HA, R_H then decreased from Aug to Oct, when SWC was also decreasing. R_H for HW increased again until Nov, again similar to SWC. From Jan to the first half of Dec, R_H for HA was never higher than R_H for HW, except for the second week of May, when HW followed the drop in SWC (Figures 4B and G).

Overall, compared to R_S, the variations in R_H were less pronounced, with differences concentrated in spring and winter, for both PA *vs* PW and HA *vs* HW (Figures 4G and H).

Annual cumulative R_S and R_H

The annual cumulative R_S were 8.97 ± 0.52 t C ha^{-1} yr^{-1} for PA and 4.67 ± 0.54 t C ha^{-1} yr^{-1} for PW, and 7.43 ± 0.72 t C ha^{-1} yr^{-1} for HA and 5.22 ± 0.68 t C ha^{-1} yr^{-1} for HW (Figure 5, total bars). The annual cumulative R_H were 4.26 ± 0.03 t C ha^{-1} yr^{-1} for PA and 3.89 ± 0.20 t C ha^{-1} yr^{-1} for PW, and 3.52 ± 0.17 t C ha^{-1} yr^{-1} for HA and 2.45 ± 0.18 t C ha^{-1} yr^{-1} for HW (Figure 5, shaded bars). For the plain site, PA showed significantly higher annual cumulative R_S and R_H compared to PW (p < 0.01). However, no differences were seen for annual cumulative R_S for the hilly sites (p > 0.05), although R_H was significantly higher for HA (p < 0.05).

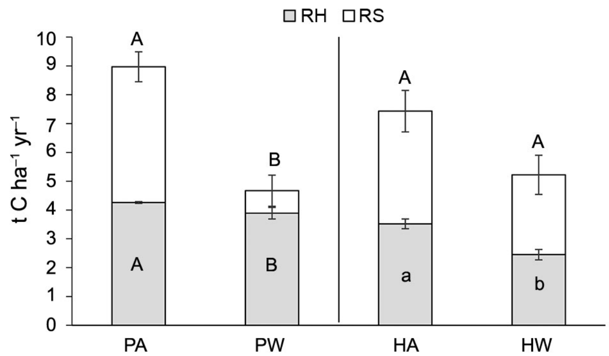

Figure 5 – Cumulative soil respiration in the different fields (PA, PW, HA, HW) of both study sites (plain, hilly) during the study period from Jan to Dec 2015. Bars represent standard errors. Different letters denote significant differences for p < 0.01 (capital letters) or p < 0.05 (small letters). PA = plain field with alfalfa; PW = plain field with wheat; HA = hilly field with alfalfa; HW = hilly field with wheat.

Relationships between soil respiration and soil temperature and water content

Over the year, no significant relationships were identified between ST (Eq. (1)) or SWC (Eq. (2)) and R_S or R_H. Instead, significant linear relationships were defined for each of the fields between the seasonal variations of R_S and R_H regarding the combination of ST and SWC (Table 2). For the plain sites, the combined model explained 49 % and 48 % of the seasonal variation of R_S, and 67 % and 36 % of the seasonal variation of R_H, for PA and PW, respectively. For the hilly sites, the model explained 49 % and 43 % of the seasonal variation of R_S, and 33 % and 58 % of the seasonal variation of R_H, for HA and HW, respectively.

Discussion

This study measured R_S and R_H in a Mediterranean environment, for which little information is available compared to other environments (Oertel et al., 2015). The soil CO_2 fluxes, mainly R_H, is correlated with mineralization of soil organic matter and thus with depletion of soil C stock (Jarvis et al., 2007; Lai et al., 2017). Peaks in soil CO_2 emissions indicate when the C flow to the atmosphere reaches its highest values, and hence when SOM mineralization occurs at the highest rates (Hanson et al., 2000).

Many previous studies have reported single peaks for soil respiration in areas with different climates. For example, in sub-tropical climates, Fan et al. (2015) reported R_S peaks for different cropping systems (including tea gardens with different management intensities,

Table 2 – Seasonal variations for R_S and R_H in combination with ST (depth, 0.1 m) and SWC (depth, 0.2 m) in different fields of both study sites. PA = plain field with alfalfa; PW = plain field with wheat; HA = hilly field with alfalfa; HW = hilly field with wheat; R_S = soil respiration; R_H = heterotrophic soil respiration.

Site	Cropping system	Soil respiration	Model equation	DF	R^2	p
			Exponential model			
Plain	PA	R_S	$y = 1.16\ e^{0.04\ ST}$	23	0.17	> 0.05
		R_H	$y = 0.38\ e^{0.06\ ST}$		0.33	> 0.05
	PW	R_S	$y = 0.54\ e^{0.04\ ST}$	23	0.23	> 0.05
		R_H	$y = 0.46\ e^{0.04\ ST}$		0.3	> 0.05
Hilly	HA	R_S	$y = 0.82\ e^{0.04\ ST}$	23	0.29	> 0.05
		R_H	$y = 0.56\ e^{0.03\ ST}$		0.24	> 0.05
	HW	R_S	$y = 1.10\ e^{0.00\ ST}$	23	0.29	> 0.05
		R_H	$y = 0.15\ e^{0.08\ ST}$		0.24	> 0.05
			Linear model SWC			
Plain	PA	R_S	y = 0.08 + 0.04 SWC	23	0.17	> 0.05
		R_H	y = 0.00 + 1.07 SWC		0.00	> 0.05
	PW	R_S	y = 0.00 + 1.25 SWC	23	0.02	> 0.05
		R_H	y = 0.02 + 1.35 SWC		0.04	> 0.05
Hilly	HA	R_S	y = 0.01 + 1.03 SWC	23	0.21	> 0.05
		R_H	y = 0.00 + 1.12 SWC		0.38	> 0.05
	HW	R_S	y = 0.05 + 0.03 SWC	23	0.22	> 0.05
		R_H	y = 0.00 + 0.81 SWC		0	> 0.05
			Combined model ST+SWC			
Plain	PA	R_S	y = -2.91 + 0.16 ST + 0.10 SWC	23	0.49	< 0.01
		R_H	y = -1.32 + 0.08 ST + 0.04 SWC		0.67	< 0.01
	PW	R_S	y = -1.56 + 0.09 ST + 0.05 SWC	23	0.48	< 0.01
		R_H	y = -0.02 + 0.04 ST + 0.01 SWC		0.36	< 0.01
Hilly	HA	R_S	y = -1.12 + 0.11 ST + 0.05 SWC	23	0.49	< 0.01
		R_H	y = -0.52 + 0.05 ST + 0.02 SWC		0.33	< 0.05
	HW	R_S	y = -2.08 + 0.07 ST + 0.08 SWC	23	0.43	< 0.05
		R_H	y = -0.84 + 0.06 ST + 0.02 SWC		0.58	< 0.01

forests, and vegetable fields) concentrated between July and Aug. Fenn et al. (2010) reported a single peak for R_S in temperate woodlands from June to July over three monitoring seasons. Tufekcioglu et al. (2001) reported R_S peaks for different crop fields (e.g., corn, soybean) and adjacent riparian buffers in a temperate climate concentrated between June and Aug. In all of these cases, the seasonal R_S patterns were associated to variations in ST, which reached peaks simultaneously with the soil CO_2 effluxes.

In line with other studies carried out in areas under a Mediterranean climate, where the highest ST values correspond to the lowest SWC values in the summer period (e.g., Almagro et al., 2009; Lai et al., 2012; Rey et al., 2002), this study shows strong seasonal variability of ST and SWC (Figures 4A-D). Moreover, in contrast to the non-Mediterranean studies mentioned above, this study shows R_S dynamics with multiple peaks (Figures 4E and F). These peaks can be explained as a combination of different management practices with variations in ST and SWC.

Soil respiration and management practices

Most studies that have investigated soil C dynamics were performed in ecosystems where human disturbance is relatively rare, such as forest ecosystems (Casals et al., 2000; Cotrufo et al., 2011; Rey et al., 2002) or other land uses (e.g., Maestre and Cortina, 2003; Munoz-Rojas et al., 2012). This study investigated soil C dynamics in 'nonequilibrium systems' and thus where management practices had major roles in soil CO_2 trends and rates, which affected both R_S and R_H. In semi-arid grasslands, mowing can suppress R_S by ceasing the substrate supply from photosynthesis to the root and rhizosphere microbes (Wan and Luo, 2003). In addition, mowing can affect ST, as the vegetation removal exposes the soil to more solar radiation and ST increment might positively stimulate the activities of microbes and plant roots (Wei et al., 2016). In line with reports by Wan and Luo (2003), R_S decreases were observed after mowing for PA and HA (Figures 4E and F). As there were no significant ST changes immediately after PA and HA mowing (Figures 4C and D), it appears that R_S decreases were related only to the effects of the mowing on the root and microbial respiration. The maximum values of R_S for PA and HA observed in late spring might have been associated with autotrophic respiration, as the removal of aboveground biomass might increase root metabolic activity (Wei et al., 2016).

In cereal-based cropping systems, soil plowing and fertilization might have major roles in soil C dynamics (Oertel et al., 2015). Nitrogen fertilization increase

R_S rates in wheat (Liu et al., 2016). For HW and PW, no R_S peaks were detected immediately after application of N fertilizer. This might be explained by the low soil organic C (Table 1), as an increase in soil N content leads to an increase in R_S when there is no limitation for the soil organic C (Micks et al., 2004; Oertel et al., 2015). R_S increases observed for the cereal-based systems here (i.e., PW, HW), which occurred roughly one month after application of N fertilizer, might be attributed to an increase in plant biomass production and stimulation of soil biological activity (Lai et al., 2012; Wang et al., 2016).

Although soil plowing alters soil porosity and bulk density, with effects on soil CO_2 efflux (Carlisle et al., 2006), for PW and HW, the soil plowing did not have any immediate effects on R_H, probably due to low SWC, which may have inhibited soil microbial activity. R_S and R_H differences observed between PA and PW and between HA and HW in autumn might be attributed to increase of microbial activities due to soil plowing that altered soil porosity (Oertel et al., 2015).

R_S and R_H dynamics observed in this study associated to the Mediterranean climate and the effects of the soil management suggest that it is possible to identify agronomic practices that limit soil C losses. For example, it is conceivable to remove the alfalfa aerial biomass produced in summer, which is usually never mowed due to adverse climate conditions that prevent hay from drying in the field. However, biomass removal might be achieved through sheep grazing alfalfa from late summer to autumn, a practice that is still followed in large-scale grazing systems of Mediterranean climate areas (Budimir et al., 2018).

Several factors affected CO_2 emissions of the cereal-based cropping system. Indeed, reduction in soil plowing depth or no tillage have different effects on soil C dynamics because they in turn affect ST, SWC and soil porosity (Bilandžija et al., 2016; López-Garrido et al., 2014). The Mediterranean climate conditions are characterized by low SWC during the summer. Thus, as well as shallower soil plowing depth (López-Garrido et al., 2014), it is conceivable that soil tillage performed in early summer might help to reduce soil CO_2 emissions, because of the limiting effect of SWC. Further soil tillage should then be performed as soon as possible to reduce soil porosity before SWC increase, which usually occurs in autumn in the Mediterranean climate areas.

Finally, to maximize the impact of specific management practices to reduce soil GHG emissions, practices should be included into agro-environmental measures at the landscape scale to involve more farmers (e.g., Toderi et al., 2017).

Annual cumulative CO_2 efflux

In general, the annual cumulative R_S emissions in this study are within the ranges reported by Raich and Schlesinger (1992) for cropland and grassland ecosystems. The cumulative R_S emission of the forage-based fields here (PA, HA) were much higher than those reported by Paustian et al. (1990) and by Gong et al. (2015) under other climate conditions (i.e., Sweden, inner Mongolia, respectively), where CO_2 rates are expected to be lower due to lower SOM mineralization rates. The annual cumulative R_S emissions of the cereal-based fields here (i.e., PW, HW) are in line with those reported by Lai et al. (2017) under similar climate conditions.

The annual cumulative R_S for the plain study site and R_H rates for both study sites were higher for alfalfa. Higher R_S and/or R_H rates are probably related to soil SOM (Table 1) and its light fraction in these fields. Previous studies have shown that the SOM light fraction increases under crop rotation, including for alfalfa, and with the number of alfalfa growing years (Wang et al., 2009; Zhang et al., 2009), while cereal-based cropping systems have detrimental effects on all organic C pools (Bongiovanni and Lobartini, 2006). Higher SOM stimulates microbial activity (García-Orenes et al., 2010; Lai et al., 2014); therefore, alfalfa fields are expected to have higher CO_2 emission rates compared to tilled cropping systems (Frank et al., 2006). In general, the continuous presence of legumes in the forage-based cropping system (Figure 2) favored a continuous supply of organic C, concurrent with a high level of available N, which leads microorganisms to degrade the SOM light fraction thus enhancing R_H (Leitner et al., 2012).

Conversely, the absence of differences in the annual cumulative R_S in the hilly sites here (i.e., HA *vs.* HW) might be attributed to the herbicide treatment in the second half of Oct for HA suppression before the sod seeding of wheat in early Nov, which might have affected both the plant root and soil microbial activities (Nguyen et al., 2016).

The soil C improvements for the forage-based cropping system, along with higher CO_2 emissions, are a considerable trade-off between the different ecosystem services (D'Ottavio et al., 2018), which require further investigations.

Effects of soil temperature and water content on soil respiration

Unlike some studies carried out under similar climate conditions (Almagro et al., 2009; Lai et al., 2012), no relationships were found here between soil CO_2 efflux and ST or SWC during the year using either exponential or linear models. While some studies have reported very high correlation coefficients between soil respiration and ST through the definition of empirical SWC thresholds (e.g., Rey et al., 2002; Almagro et al., 2009; Lai et al., 2012), all attempts to use empirical threshold values for SWC did not result in better correlation coefficients for R_S or R_H for any of these study fields (data not shown). If, on the one hand, there is no clear relationship between soil respiration drivers and CO_2 emissions during the entire year; on the other hand, there emerges a strong relationship between ST and CO_2 only for the first part of the year (i.e., from Jan to June for PA-HA, from Jan to May for PW-HW), as reported by other studies under Mediterranean climate conditions (e.g., Rey et al., 2002). In this case, ST was the main driver of soil CO_2 emissions, as a simple exponential model (Eq. (1)) explained 82 % ($p < 0.01$), 82 % ($p < 0.05$), 80 % ($p < 0.01$), and 68 % ($p < 0.05$) of the seasonal variations of R_S in PA, PW, HA, and HW, respectively. During the same period, the exponential model explained 78 % ($p < 0.01$) and 84 % ($p < 0.01$) of the seasonal variation of R_H in PA ad HA, respectively, while no significant relationships were observed for PW ($R^2 = 0.38$; $p > 0.05$) and HW ($R^2 = 0.55$; $p > 0.05$). For the rest of the year, R_S and/or R_H did not only depend on ST and SWC, as other factors had major roles, which may have been either biotic factors, such as microbial or enzyme activities (Almagro et al., 2009; Fan et al., 2015; Lai et al., 2014; Wang et al., 2016), and abiotic factors, such as soil disturbance (e.g., soil tillage) or changes to vegetation (e.g., mowing) (Lai et al., 2012; Liang et al., 2015; Ryan and Law, 2005), as previously discussed. This implies that modeling soil respiration under these Mediterranean climate conditions tends to be difficult, especially if only ST and SWC are the factors considered (Cotrufo et al., 2011; Lai et al., 2012; Oyonarte et al., 2012), as during the summer, low SWC has a major role in inhibiting both R_S and R_H (Davidson et al., 1998; Xu and Qi, 2001). In addition, ST and SWC often vary together and this co-variation prevents the emergence of clear relationships with R_S and/or R_H (Davidson et al., 1998; Rey et al., 2002). Nevertheless, in this study, the two-variable model that combined ST and SWC did explain 43 % to 49 % and 33 % to 67 % of the annual variations for R_S and R_H, respectively. These values appear to be slightly below those reported in other studies carried out under similar climate conditions (Rey et al., 2002; Almagro et al., 2009). For example, for PA, the ST-SWC combined model was the best R_H predictor due to the absence of soil disturbance ($R^2 = 0.67$; $p < 0.01$). Conversely, for the same study site, the same model explained only 36 % of the annual variation of PW R_H. This was mainly due to management practices usually carried out in these cropping systems (i.e., fertilizer, soil plowing, mowing, herbicides), which affect R_S and R_H (Carlisle et al., 2006; Wan and Luo, 2003; Wei et al., 2016), and consequently introduced bias into the model.

Conclusions

In this study, R_s and R_H showed different dynamics, with spatial and temporal variability across these study sites. The forage-based cropping system (alfalfa) showed higher annual cumulative R_S only for the plain area site (PA). Conversely, and probably due to herbicide effects on alfalfa R_S, there were no differences for the hilly site (HA). The forage-based cropping systems (PA, HA) showed higher annual cumulative R_H, as well as higher SOM and total organic C accumulation. The model with ST and SWC combination provided better prediction for R_S and R_H variation for all study sites, when compared to single ST or SWC modeling over the year, or to models that use empirical threshold values.

Although these findings contribute towards filling some gaps in knowledge of cropping systems under Mediterranean climate conditions, further studies should focus on drives of R_S and R_H. Thus, further studies on soil C dynamics should increase the effects of common management practices, particularly regarding areas under Mediterranean climate conditions, where the data are relatively fragmented and controversial and where they have mainly addressed systems with limited human disturbance.

Authors' Contributions

Conceptualization: Francioni, M.; Lai, R.; D'Ottavio, P.; Toderi, M. Data analysis: Francioni, M.; Trozzo, L. Design of methodology: Francioni, M.; Lai, R.; D'Ottavio, P.; Toderi, M. Writing and editing: Francioni, M.; Lai, R.; D'Ottavio, P.; Toderi, M.; Kishimoto-Mo A.W.; Baldoni, N.; Budimir, K.

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