

SOIL RESPIRATION DYNAMICS, AS A NEW APPROACH IN NATURE-BASED SOLUTIONS FOR THE REDUCTION OF GREENHOUSE GAS FLUXES IN THE TERRESTRIAL BIOSPHERE

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Abstract. Soil respiration (Rs) is a major component of an ecosystem carbon cycle. To quantify soil CO₂ efflux, field experiments were conducted *in situ* (2015–2017) with an LCi-SC soil CO₂ flux system under three semi-arid ecosystems in the Mediterranean as one of the main identified climate change hotspot. Mean values of Rs rates showed that soil CO₂ effluxes were significantly different among various terrestrial ecosystems with higher Rs in semi-natural ecosystems as under Steppe $1.739 \pm 0.717 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ($658.093 \pm 271.336 \text{ g C m}^{-2} \text{ yr}^{-1}$) and under Forest $4.205 \pm 1.731 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ($1591.307 \pm 655.066 \text{ g C m}^{-2} \text{ yr}^{-1}$) than under the natural ecosystem Garrigue $0.914 \pm 0.309 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ($345.887 \pm 116.935 \text{ g C m}^{-2} \text{ yr}^{-1}$). It appears that soil CO₂ efflux is highly ecosystem-specific, so it is required to be verified across ecosystem types. We recorded a very strong relationship between Ts and Ws, as documented by the correlation coefficient ($r = -0.848$), respectively *R*-squared (71.908%). Our results show that the natural ecosystem Garrigue under climate warming could release less CO₂ efflux than semi-natural ecosystems and each semi-arid ecosystem can emit different amounts of CO₂ emissions under the same environmental conditions.

Keywords: CO₂ efflux, soil respiration, ecosystem, climate change.

AIMS AND BACKGROUND

According to the Paris Climate Agreement, we must significantly reduce greenhouse gas emission, and it must go hand in hand with sustainable green infrastructure development by 2030 (Ref. 1). Terrestrial ecosystems act as a significant global

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carbon sink while storing large amounts of carbon into living vegetation and soils^{2,3}. The primary pathway where CO₂ returns to the atmosphere is Soil respiration (Rs), representing 60–90% of the total ecosystem respiration. Therefore, Rs is a major source of soil carbon dioxide released by terrestrial ecosystems⁴ and plays major role in regulating atmospheric CO₂ concentration and climatic dynamics in the earth system^{4–6}. Relatively small anthropogenic changes in ecosystem management and associated changes in the extent of CO₂ emissions in the soil have a massive impact on atmospheric CO₂ concentrations and can lead to significant feedback to exacerbate or reduce rising CO₂ in the atmosphere^{7–10}. The Mediterranean region, due to its location and the geographical factors associated with, is considered as a ‘hot-spot’ of both biodiversity and climate change, having been identified in global climate scenarios as one of the most responsive regions to climate change¹. The quantification of CO₂ effluxes as they occur in the various terrestrial ecosystems has been identified as the key gap in expertise in the context of sustainable landscape management^{11–15}.

The specific objectives of this study, therefore, were to: (i) to investigate carbon dioxide flux in Rs and its relationship to ecosystem types in Xrobb L-Għażiex Nature park (Malta, EU); (ii) to investigate seasonal variations in soil respiration of three representative terrestrial ecosystems in a dry and wet (growing) season in Mediterranean, and (iii) to clarify the Rs dependences on abiotic factors such as temperature and moisture. This study specifically sets out to investigate the different variations in Rs, of a seasonal nature, among different ecosystems, with a special focus on dissimilarities between natural ecosystems (Garrigue) and semi-natural ecosystems (Steppe and Forest (afforested area in 2005).

EXPERIMENTAL

Study site and vegetation. The study was conducted from December 2015 to February 2016 and July to August 2016 and December 2016 to February 2017 and July to August 2017 on three terrestrial ecosystems (Garrigue (E1), Steppe (E2) and Forest (afforested area – semi-natural ecosystem) (E3) in Xrobb L-Għażiex Nature park (35°50'30"N and 14°34'11" E in DMS (Degrees Minutes Seconds) or 35.8417 and 14.5697 (in decimal degrees), a peninsula of 155 950 m², circa 230 m above sea level), in Malta (Europe). The climate is the Mediterranean according to the Köppen climate classification (Csa)¹⁷, with two main seasons: a hot and dry summer with mean annual temperature of 28 (82°F) during the day and 20°C (68°F) at night and a mild wet winter with mean annual temperature of 16°C (61°F) during the day and 10°C (50°F) at night. Malta has an average of 90 precipitation days a year, and experiences from a few to a dozen rainy days per month (≥ 1 mm), ranging from 0.5 of a day in July to around 15 in December. The

average annual precipitation is around 600 mm, ranging from ~0.3 mm in July to ~110 mm in December¹⁶.

According to the dominant natural vegetation in the Xrobb L-Għagin Nature park, three ecosystems were selected in terms of vegetation composition, including one natural ecosystem: Garrigue (E1) (was coordinated N 35.84278° E 14.56865°) covered by dominant patches include those of the indigenous *Senecio cineraria*, *Convolvulus oleifolius* Desrousseaux and *Suaeda vera*, *Golden Samphire* and two semi-natural plot – Andropogonid Steppe (E2) (was coordinated N 35.84372° E 14.56652°) dominated by *Antropogon distachios* and an afforested area (E3) (was coordinated N 35.84313° E 14.56573°) containing *Pinus halepensis* (planted in 2005) (Refs 17 and 18). According to FAO soil taxonomy, there is mainly Terra Rossa Soil¹⁷.

Sampling strategy. Soil respiration was measured using the LCi-SC (Ref. 19) fitted with a dynamic closed chamber to measure *in situ* CO₂ fluxes with a portable CO₂ analyser. The collar insertion pad was installed 0.08 m into the soil for at least a day before results were taken in earnest to avoid a major soil disturbance. The collar was only inserted once, avoiding further soil disturbance, which is known to upset soil respiration. To avoid the effects of the time of R_s, we standardises the time at which R_s is measured at 8 a.m. local time. Mean values of CO₂ efflux represented the average value of 20 measurements at weekly intervals for up to 10 weeks during sunny days in two dominant aspects of the Mediterranean year (dry summer and wet winter aspects) in 2015, 2016 and 2017.

Soil temperature (T_s) and soil volumetric water content (W_s) were measured at a depth of 0.08 m at each sampling point with an LI-6400 and W_s with a time domain reflectometry device (TDR multiple-level thermocouple sensors).

Data and statistical analyses. The data of CO₂ exchange rates presented in this paper were converted from $\mu\text{mol m}^{-2} \text{s}^{-1}$ to $\text{g C m}^{-2} \text{yr}^{-1}$ as it is more commonly used for data presentation.

The dependence of W_s relation on T_s and also the soil respiration relation on W_s and T_s were evaluated by the statistical method of simple linear regression.

Repeated measure analyses of variance (ANOVA) were conducted with soil CO₂ fluxes, soil moisture and temperature and with seasonal aspects as independent factors. Soil respiration results were elaborated with software package Statgraphic version 5.0 by three-factor variance analysis (multifactor analysis of variance), whereby an evaluation was made of the ecosystem type (E1, E2 and E3) and the annual aspects (summer dry, and winter wet growing aspect). Statistical evidence of differences was evaluated by the LSD test at 95% level of proficiency.

RESULTS AND DISCUSSION

Seasonal variation in soil temperature and soil moisture. The average temperature showed no significant difference in studied ecosystems during the study periods. The highest recorded daily mean of T_s was in summer 2017 (E1 = 27.5°C, E2 = 27.07°C, E3 = 24.69°C) and the lowest was in winter 2016 (E1 = 10.64°C, E2 = 10.56°C, E3 = 10.20°C). Soil moisture content varied largely over the study periods, ranging from 5.3 to 16.1% (E1), from 5.0 to 15.4% (E2) and from 4.4 to 14.9% (E3) (Figs 1 and 2). Mean annual precipitation was mostly identical during the study periods (lowest in 2015 (563 mm) and highest in 2016 (570 mm)). W_s at 0–0.08 m depth was below 10% during July and August except after occasional rainfall events, when it increased sharply. W_s rates exhibit a large seasonal variation and decrease with increasing T_s . W_s was correlated negatively with T_s , we recorded a very strong relationship, as documented by the correlation coefficient ($r = -0.848$), respectively R -squared (71.908%). In addition, W_s in the afforested area (E3) was consistently lower than in the other ecosystems throughout the study period. Both T_s and W_s varied markedly with season among each of the three experimental fields.

T_s is regarded as the primary abiotic control element on Rs, whereas W_s is the secondary control element. However, in conditions of extreme moisture or, on the other hand, of extreme dryness, W_s can constitute the main control on Rs. The results obtained from studies investigating the degree of impact of drought on Rs have been inconsistent^{15,20,21}. In our study, the seasonal courses of Rs generally followed the seasonal cycle of W_s , but moderated by soil temperature. The correlation between the dependence of the Rs relation on W_s and T_s was evaluated by the statistical method of simple linear regression. We recorded a slightly tight relationship between Rs and the soil moisture, as documented by the correlation coefficient ($r = 0.3967$), respectively R -squared (15.735%). Between Rs and T_s , we recorded a slightly tight relationship, as documented by the correlation coefficient ($r = -0.4901$), respectively R -squared (24.0221%).

Seasonal dynamics of soil respiration rate in three terrestrial ecosystems. The observed variation of Rs for the three terrestrial ecosystems followed the change of W_s over the study period. Generally, Rs was higher during the growing wet seasons (winter aspect) and lower in dry seasons (summer aspect) (Figs 1 and 2). Rs reached their highest values in December overall seasons of the study period, and due to higher precipitation in December 2016, the Rs showed the highest peak in each ecosystem type. The field measurement data encompassed a wide range of R_s during the study period (2015–2017), which were $0.914 \pm 0.309 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ($345.887 \pm 116.935 \text{ g C m}^{-2} \text{ yr}^{-1}$) for the E1, $1.739 \pm 0.717 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ($658.093 \pm 271.336 \text{ g C m}^{-2} \text{ yr}^{-1}$) for the E2 and $4.205 \pm 1.731 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ($1591.307 \pm 655.066 \text{ g C m}^{-2} \text{ yr}^{-1}$) for the E3 (Figs 1 and 2). The ecosystem type had significant influences to affect the terrestrial carbon dynamics on Rs ($P < 0.05$).

R_s was significantly lower in the Garrigue (E1) than in the Steppe (E2) ($P < 0.05$) and in the Forest (E3) ($P < 0.05$) throughout each year during the study periods, indicating a dominant control of root-associated respiration over R_s . However, it should be noted that this study was of an observational, non-manipulative nature. Furthermore, it should also be noted that the three sites selected in the experiment were situated adjacent to each other and that the afforested area was originally similar to adjacent natural ecosystems. R_s for E1 varied from 0.61 ± 0.13 (dry summer aspect) to 1.12 ± 0.21 (wet winter aspect), for E2 from 0.91 ± 0.18 (dry summer aspect) to 2.29 ± 0.25 (wet winter aspect) and for E3 from 2.15 ± 0.13 (dry summer aspect) to 5.58 ± 0.45 (wet winter aspect) $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, respectively. R_s values of wet winter seasons (December–February) showed a significant difference from those of dry summer seasons (July–August) ($P < 0.05$) (Table 1).

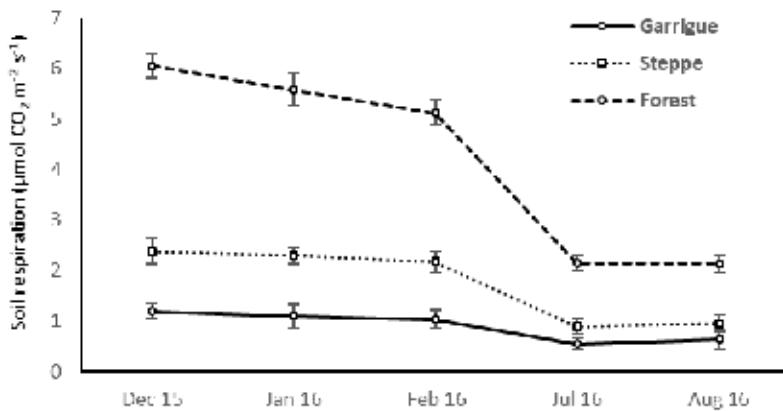


Fig. 1. Effect of the various terrestrial ecosystems on seasonal soil respiration dynamics across measurement periods 2015–2016

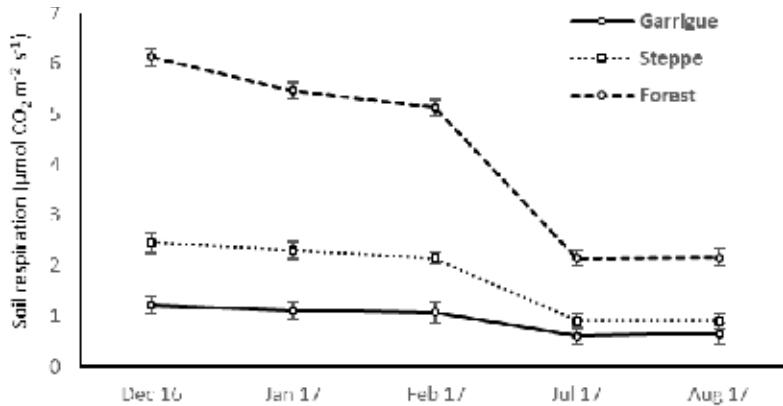


Fig. 2. Effect of the various terrestrial ecosystems on seasonal soil respiration dynamics across measurement periods 2016–2017

Table 1. Seasonal dynamics of soil respiration rates ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) in the three ecosystems across measurement periods

Year	Ecosystem type		Month
2015/2016	2.282 \pm 1.784 a	E1	0.914 \pm 0.309 a
2016/2017	2.290 \pm 1.778 a	E2	1.739 \pm 0.717 b
		E3	4.205 \pm 1.731 c
		July	1.207 \pm 0.700 a
		August	1.239 \pm 0.681 a
		February	2.778 \pm 1.756 b
		January	2.972 \pm 1.908 b
		December	3.233 \pm 2.115 b
LSD $\alpha_{0.05}$	0.188055	0.394957	0.725185

Statistic method: Multifactor ANOVA – 95.0% LSD test ($\alpha = 0.05$). The values in the same column with different letters a, b, c are significantly different at $P < 0.05$ level.

According to our results, there was the statistical significance of the R_s peaking in the wet (winter) season and then decreasing in the dry (summer) season during the study periods in each studied ecosystem (Table 1, Figs 1 and 2). These results contrast with those reported by Lai et al.¹³ and Chang et al.²¹ where seasonal variability in R_s was mainly controlled by temperature with maximum rates in summer. Our study did not confirm that R_s increases exponentially with T_s increase. We also found out a positive linear relationship between W_s and the rate of R_s . Several authors suggest that under certain conditions, precipitation and/or soil moisture significantly influence respiration^{21–22}. The positive linear relationship between R_s and W_s in low soil moisture conditions found in our work agrees with many previous studies where low soil moisture constrains R_s (Refs 4 and 15). Our results showed that the low soil moisture and higher soil temperatures actually reduced R_s rates. Such a relationship is in agreement with other previous similar studies^{4,13,15}.

The mean values of annual soil respiration recorded by Raich and Schlesinger²⁴ for different ecosystems were of $442 \text{ g C m}^{-2} \text{ yr}^{-1}$, $224 \text{ g C m}^{-2} \text{ yr}^{-1}$ and a mere $60 \text{ g C m}^{-2} \text{ yr}^{-1}$ for temperate grasslands, desert scrub and tundra, respectively. Similar results have been reported by Lai et al.¹³ for side-by-side comparisons of five different plant ecosystems. However, when compared to the values obtained in measurements taken across various sites as part of the EUROFLUX study ($760 \pm 340 \text{ g C m}^{-2} \text{ yr}^{-1}$), they would be among the higher range of measurements obtained therein²³.

On each of the studied terrestrial ecosystems, we found ecosystem respiration to be strongly stimulated by winter rains following the summer drought; this had the effect of inducing a positive CO_2 flux to the atmosphere. Lai et al.¹³ also noted that seasonal differences in R_s could be large. Our study demonstrates that each ecosystem under the same environmental conditions can emit different quantities of CO_2 from the soil.

Climate models indicate that arid and semiarid ecosystems will be strongly affected by changes in temperature and precipitation within this century. These changes have become very important in the Mediterranean, where water availability is a key driver for ecosystem functioning and understanding the responses of terrestrial ecosystems to global environmental change is a major challenge of current ecological research^{1,3,13,21,22}.

CONCLUSIONS

According to our results, the main conclusions are as follows:

(i) The soil CO₂ emissions were significantly different among terrestrial ecosystems, being significantly lower in the Garrigue (E1) than under the Steppe (E2) and Forest (E3) throughout each main season and each study year. Rs was significantly the highest in the Forest in dry summer as well as wet growing winter season in each study year. This difference would be mediated through a vertical gradient of soil activity in each studied terrestrial ecosystem (there were identical soil types), not through variations in T_s and W_s since it was not significantly different among the ecosystem types. Precipitation obviously influenced Rs, after heavy rain occurred; soil water content rather than soil temperature significantly influenced Rs. This indicates that the CO₂ efflux under the natural ecosystem Garrigue under climate warming could release less than under semi-natural ecosystems Steppe and the Forest containing *Pinus halepensis*. However, it appears that soil CO₂ efflux is highly ecosystem-specific, so it is required to be verified across ecosystem types.

(ii) Soil CO₂ effluxes showed significant seasonal variations corresponding to T_s and W_s changes. W_s at 0.08 m depth indicates the dominant control on the seasonal variations of Rs in each of three terrestrial ecosystems. The W_s rates exhibit a large seasonal variation and decrease with increasing T_s .

(iii) The Rs tends to increase with increasing W_s in the wet growing season in each terrestrial ecosystem. The interactions of T_s and W_s content had a slightly tight relationship to the soil CO₂ efflux.

Given its arid and semi-arid climate, the Mediterranean region is a suitable area to study the effects of drought on Rs. The variation of different ecosystems on the terrestrial carbon balance in outgoing climate change is predicted to be large. It is therefore critical to control and eliminate carbon emissions from Rs to the atmosphere. Greater attention is needed to reduce CO₂ emissions from each ecosystem operation when changing the natural ecosystem to the semi-natural ecosystem in connection with the integration of greenhouse gas (GHG) mitigation strategies in the context of sustainable landscape management.

ETHICAL STANDARDS

We declare that the experiments comply with the current laws of the Maltese Islands. Nature Trust (Malta) gave us the authorisation to study Rs in Xrobb L-Għagin Nature Park. We used a non-invasive research method *in situ*, and no plants were damaged during this research.

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