

1 **Detail response to two Reviewers comments, BG-2019-291**  
2

3 We thank the reviewers for their constructive comments we provide a point by point response  
4 below. Note that in general, considering the comments on confusing text, we significantly reduced  
5 the text, removing all non-essential parts and sent the manuscript for professional proof editing  
6 (Scribandi.com). This included the following changes:

- 7 1. Deleting Table 4 (non-essential long-term regressions)
- 8 2. Revising Table 3 for clarity including the ratio between the present study and 2003 (mean of  
9 2001-2006).
- 10 3. We added material to SI: Expanded Fig. SI-1 as discussed below. New Fig. SI-5 as discussed  
11 below. New Fig. SI-8 on heterotrophic and soil respiration as a function of precipitation (based  
12 on literature, and used in the Discussion). We added Table SI-3 on literature compilation of  
13 background data (used in the Discussion).

14 We believe these major revisions together with response detail below greatly improved the  
15 focus and clarity of the paper and address all points raised by the reviewers. We hope the paper  
16 is now ready for final publication.

17  
18 **Ref1**

19  
20 This paper uses soil and canopy fluxes with stable isotopes ( $^{13}\text{C}$ ) and radiocarbon( $^{14}\text{C}$ )  
21 measurements of a 50-year-old dry pine forest over one year to partition the ecosystem's  $\text{CO}_2$   
22 flux into gross primary productivity (GPP) and ecosystem respiration( $R_e$ ) and soil respiration  
23 flux into autotrophic ( $R_{sa}$ ), heterotrophic ( $R_h$ ), and inorganic( $R_i$ ) components. The  
24 measurements and data are valuable. The topics are be of great interest.

25  
26 **Response:** Thank you, it is the most important point. But as we clarify better in the revisions  
27 (see also below) the paper goes beyond “one year of partitioning” as this year of measurements  
28 allowed us to combine it with our study 10 years earlier at the same site to provide a longer-term  
29 perspective on the changes in such partitioning (and as the saying goes, with the “whole is  
30 greater than the sum of its parts”...)

31  
32  
33  
34 But the writing is very confusing.

35  
36 **Response:** We are sorry this is the case and made a serious effort to fix this by better  
37 streamlining the paper (as also noted below), careful proof-reading and, considering that the  
38 authors are not native English speakers, also sending it out to professional editing.

39  
40  
41  
42 Abstract: The abstract lacks critical information.

43  
44 **Response:** We are not sure what is the missing critical information. We added in the Abstract  
45 key information on the site and the study itself. And additional key results after we carefully  
46 compared the Abstract and the Result. The results are presented in 3 figures and 4 tables, and  
47 carefully comparing the detail summary of the results in the Abstract, indicates that all the main

48 points, including our observed values of GPP, Re, NPP, CUE, the partitioning (the main effort in  
49 this study) of respiration  $R_s$  to  $R_{sa}$  to  $R_h$ ,  $R_i$ , the seasonal changes, the main long-term  
50 changes when combined with our earlier study, and the main occlusions.

51  
52  
53

54 Introduction: The introduction should be rephrased. There are too much pieces of information on  
55 general knowledge. The Introduction needs a better flow. The scientific significance should be  
56 addressed more. A description that explain why the paper is needed following the previous  
57 studies (i.e. the 2001-2006 study) would be very informative for the readers. Furthermore, I  
58 suggest the authors cite more relevant papers on the Mediterranean climate zones and add one  
59 or two hypothesis.

60  
61 **Response:** Done. We shortened the introduction by removing two non-critical paragraphs,  
62 which simplify it. We also improved the Motivation at the end of the Intro, and we provide clearer  
63 working hypotheses, as requested. We checked the literature and added missing references on  
64 Mediterranean studies.

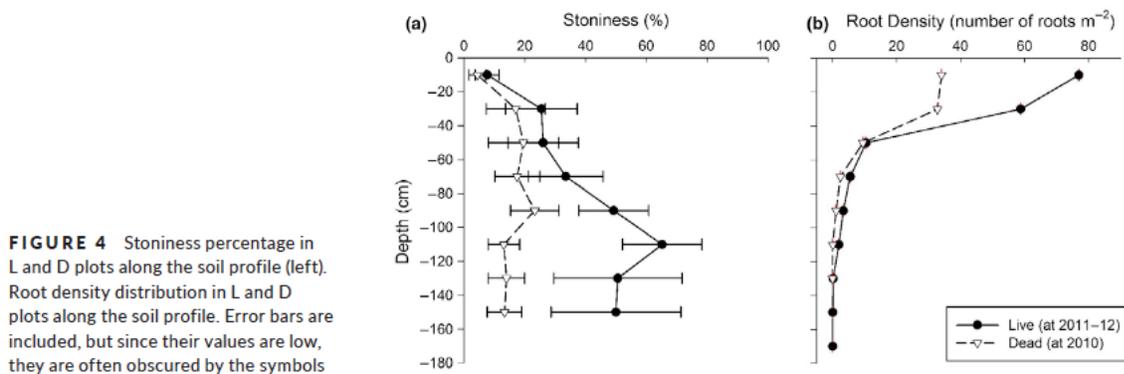
65  
66  
67

68 Site description: provide more information about the vegetation (e.g. root depth). Flux and  
69 meteorological measurements: How did the gaps in NEE and GPP are filled? How many  
70 missing data points are there due to instrument failure and quality control?

71  
72

73 **Response:** Done. We added the requested information, including detail on root depth and on  
74 the vegetation at the site (overstory and understory, indicating the main species). Specifically,  
75 technical details of “gap filling” indicated and a paper with more detail is cited. We also added  
76 information on root depth and note that more detail is provided in our paper published earlier  
77 this year (Preisler et al. 2019, Functional Ecology; now cited):

77



78  
79  
80

81 Soil CO<sub>2</sub> flux: I'm really confused. How many data did the author used in the paper? Just one  
82 year? Using just one-year measurements can not identify the long-term temporal changes in the  
83 soil-atmosphere CO<sub>2</sub> fluxes in this environment.

84

85 **Response:** As noted above, we now clarify this issue straight-out in the Intro and again in the  
86 Methods and in the Discussion. Briefly, note that all the figures and tables indicate that the new  
87 data were obtained during **2015-2016** (one full year). But both the figures/tables and Discussion  
88 show that important virtue of the paper is in combining these new data with our earlier study at  
89 the same site (**2001-2006**) looking at the same parameters and providing the opportunity to  
90 obtain a long-term perspective of the change in the flux component (i.e. in the partitioning) over  
91 a time window of about 10 years. Many of the studies reported in this journal aim at assessing  
92 change, especially in response to global change. While some parameters are monitored  
93 continuously (our flux tower operated continuously for 20 years), other measurements required  
94 for the Partitioning of soil fluxes cannot, practically, be made continuously and here we combine  
95 the continuous measurement with the periodical campaign to assess sufficiently long-term  
96 changes.

97  
98  
99  
100 Discussion: The hypothesis should also be into Introduction. The present study used only one-  
101 year data, I suggest the authors using a tempered tone in the discussion part. The Discussion  
102 has the same problem with Introduction. There are many pieces of interesting information. But  
103 the discussion should be centered on several key aspects of your results. The Discussion  
104 should echoes the Introduction. I suggest rephrase the Discussion and make a better flow in the  
105 Discussion.

106  
107 **Response:** Done. The working Hypotheses are included in both the Introduction and  
108 Discussion as noted above, and we streamlined the Discussion deleting some non-critical parts  
109 and to improve the correspondence with the Introduction. As also noted above, we better focus  
110 on the link of the new data of this study with our older study at the same site over 10 years ago  
111 to assess changes to address the issue of changes in the ecosystem and particularly in the soil  
112 carbon flux component over time (we also added in the SI the long-term records of temperature  
113 and precipitations).

---

114  
115  
116  
117 **Ref2**

118  
119 This manuscript describes the study partitioning of canopy and soil CO<sub>2</sub> fluxes in a pine forest  
120 at the dry timberline using the measurements of isotopic signatures ( $\delta^{13}\text{C}$  and  $\Delta^{14}\text{C}$ ) of CO<sub>2</sub>  
121 emitted from bulk soils, fine roots, root-free soils, and carbonate fractions. The measurement  
122 and data are interesting. Then, scientific insights, which can be gained from this study, would  
123 significantly contribute for improving our under-standing the response of dry environment  
124 ecosystems to climate change.

125  
126 **Response:** Thank you. It is important to see that this study is recognized as adding to  
127 understanding ecosystem response to change.

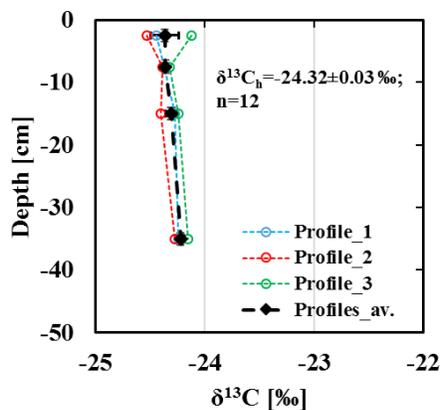
128  
129  
130  
131 The writing, however, should be improved more and more as pointed out by Referee #1. Then,  
132 please refine every sentence in the manuscript more carefully, because there are substantial

133 typos (e.g. “a pine forests” in the title, “Soil respiration from the atmosphere” in Line 29-30,  
134 “Reflux” in Line 369, and so on).

135  
136 **Response:** We recognize that our failure to submit an appropriately proofed manuscript made  
137 some significant damage, although there were no errors in the science. This was the result of  
138 some unfortunate confusion in combining the different versions of the paper proof-read by  
139 different coauthors. It has been fixed and considering that the authors are not native English  
140 speakers the paper has been sent out for professional editing.

141  
142  
143  
144 In addition to these concerns for writing, I have a technical concern about the estimating  $\delta^{13}\text{C}$   
145 for  $\text{CO}_2$  emitted from bulk soils (i.e.  $\delta^{13}\text{C}$  RS in the manuscript). The authors estimated  $\delta^{13}\text{C}$   
146 RS using the keeling plots for soil  $\text{CO}_2$  profile data at 0, 30, 60, 90, and 120 cm depth; however,  
147 the  $\delta^{13}\text{C}$  of soil organic matters, the major source of heterotrophic respiration, often change  
148 along with soil depth increase. Then, these vertical changes in  $\delta^{13}\text{C}$  of soil organic matters have  
149 significant potentials affecting the  $\delta^{13}\text{C}$ - $\text{CO}_2$  profile. This means that the observed relationships  
150 between  $\delta^{13}\text{C}$ - $\text{CO}_2$  and  $\text{CO}_2$  concentration profiles might be affected not only by the change in  
151 contribution of source  $\text{CO}_2$  and background  $\text{CO}_2$ , but also by the changes in  $\delta^{13}\text{C}$  of source  
152  $\text{CO}_2$ . Therefore, in my opinion, the authors are needed to provide the reliable justification for  
153 their methodology, to quantify the uncertainty for estimated  $\delta^{13}\text{C}$  RS, and/or to apply alternative  
154 methodology for estimating  $\delta^{13}\text{C}$  RS.

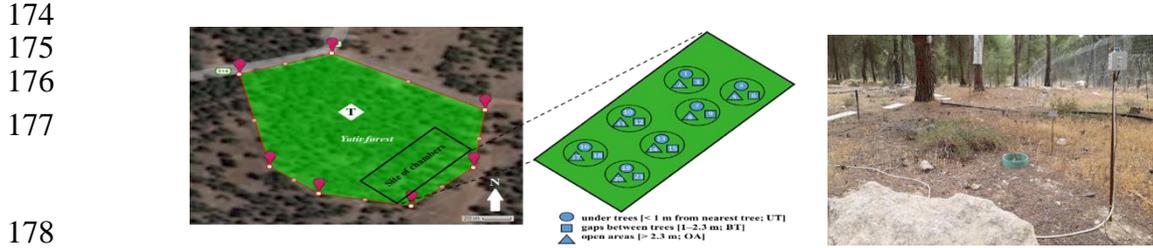
155  
156 **Response:** This is indeed an important point and has now been clarified in the revisions. The  
157 Ref is correct in noting that the Keeling plot approach is based on 2-end members mixing (as  
158 also explained in the Review one of us co-authored; Pataki et al., 2003), and in many cases this  
159 assumption does not hold in soils. However, it seems that the very dry conditions at our study  
160 site gave us an opportunity to avoid this caveat. As shown in the figure below, there is  
161 essentially no change in  $^{13}\text{C}$  of soil organics with depth (SD of the 12 samples = 0.12 permil).  
162 This is likely because the dry conditions strongly constrain decomposition and probably also the  
163 range of microbial populations (and help explain the high soil carbon storage in this system as  
164 noted in the Discussion). It therefore seems that the soil  $\text{CO}_2$  samplings we carried out still  
165 represent predominantly the mixing of atmospheric  $\text{CO}_2$  with one integrated soil source signal.  
166 We must conclude of course that the variations among the contributions of  $R_{\text{sa}}$ ,  $R_{\text{h}}$ , and  $R_{\text{i}}$  do  
167 not change significantly with depth and the single set of isotopic signatures in Table 2.



168

169 Finally, please consider to include the photographs showing conditions of each chamber site  
170 and the schematic diagrams describing three collars locations within a chamber site

171  
172 **Response:** We are happy to oblige and agree this could help. We added to the SI diagram and  
173 photo.



190

191

192

193 **Partitioning of canopy and soil CO<sub>2</sub> fluxes in a pine ~~forests~~forest at the dry**  
194 **timberline across a 13-year observation period**

195 Rafat Qubaja<sup>a</sup>, Fyodor Tatarinov<sup>a</sup>, Eyal Rotenberg<sup>a</sup>, and Dan Yakir<sup>a\*</sup>

196 <sup>a</sup> Department of Earth and Planetary Sciences, Weizmann Institute of Science, Rehovot 76100, Israel

197 \*Correspondence: Dan Yakir; email: [dan.yakir@weizmann.ac.il](mailto:dan.yakir@weizmann.ac.il)

198 **Abstract**

199 Partitioning carbon fluxes is key to understanding the process underlying ecosystem response to change.  
200 This study used soil and canopy fluxes with stable isotopes (<sup>13</sup>C) and radiocarbon (<sup>14</sup>C) measurements ~~of~~  
201 ~~in an 18 km<sup>2</sup>, 50-year-old dry (287 mm ~~of mean~~ annual precipitation)-~~pine; non-irrigated~~ *Pinus halepensis*~~  
202 forest plantation in Israel to partition the net ecosystem's CO<sub>2</sub> flux into gross primary productivity (GPP)  
203 and ecosystem respiration (Re) and (with the aid of isotopic measurements) soil respiration flux (Rs) into  
204 autotrophic (Rsa), heterotrophic (Rh), and inorganic (Ri) components. On an annual scale, GPP and Re  
205 ~~were measured~~ 655 and 488 g C m<sup>-2</sup>, respectively, with a net primary productivity (NPP) of 282 g C m<sup>-2</sup> and  
206 carbon-use efficiency (CUE=NPP/GPP) of 0.43. ~~Rs~~ made up 60% of the ~~total ecosystem respiration~~Re  
207 and ~~was comprised of~~ 24 ± 4%, 23 ± 4%, and 13 ± 1% ~~% from~~ Rsa, Rh, and Ri, respectively. The  
208 contribution of root and microbial respiration to Re increased during high productivity periods, and  
209 inorganic sources were more significant components when the soil water content was low.  
210 ~~Compared~~Comparing the ratio of the respiration components to theRe of our mean 2016 values to those of  
211 2003 (mean for 2001–2006) at the same site; indicated a ~~Grünzweig et al., 2009~~, ~~annual Rs decreased by~~  
212 ~~27% to the mean 2016 rates of 0.8 ± 0.1 μmol m<sup>-2</sup> s<sup>-1</sup>). This was associated with~~ decrease in the respiration  
213 Q<sub>10</sub> values ~~autotrophic components (roots, foliage, and wood) by about -13%, and an increase in the~~  
214 heterotrophic component (Rh/Re) by about +18%, with similar trends for soil respiration (Rsa/Rs

215 ~~decreasing by -19% and Rh/Rs increasing by +8%, respectively). The soil respiration sensitivity to~~  
216 ~~temperature ( $Q_{10}$ ) decreased~~ across the same observation ~~period~~ by 36-% and 9-% in the wet and dry periods,  
217 respectively. Low rates of soil carbon loss combined with relatively high ~~below ground~~~~belowground~~ carbon  
218 allocation (i.e., 38% of canopy CO<sub>2</sub> uptake) ~~and low sensitivity to temperature~~ help explain the high soil  
219 organic carbon accumulation and the relatively high ecosystem CUE of the dry forest. ~~This was indicative~~  
220 ~~of the higher resilience of the pine forest to climate change and the significant potential for carbon~~  
221 ~~sequestration in these regions.~~

222  
223 **Keywords:** Carbon balance, Soil respiration, Autotrophic, Heterotrophic, Inorganic flux, Temperature  
224 response, Semi-arid ecosystem, Pine forest, Canopy cover, Soil chamber

## 225 1. Introduction

226 ~~On a global scale, soil stores over 1,500 Pg of carbon, which is more than the atmosphere and terrestrial~~  
227 ~~plant biomasses combined (Köchy et al., 2015; Le Quéré et al., 2018; Scharlemann et al., 2014). Soil~~  
228 ~~respiration (Rs) from terrestrial ecosystems and the atmosphere constitutes a large part of the terrestrial~~  
229 ~~carbon cycle (Le Quéré et al., 2018), releasing 68–98 Pg C into the atmosphere as CO<sub>2</sub> annually (Adachi et~~  
230 ~~al., 2017; Hashimoto et al., 2015; Zhao et al., 2017). This is far more than fossil fuel emissions by an order~~  
231 ~~of magnitude (Ballantyne et al., 2015).~~

232 The annual net storage of carbon in ~~the land biospheres~~biosphere, known as net ecosystem production  
233 (NEP), is the balance between carbon uptake during gross primary productivity (GPP) ~~and~~ and carbon loss  
234 during growth ~~and~~ maintenance respiration by plants (i.e., autotrophic respiration ~~[, Ra])~~ and  
235 decomposition of litter and soil organic matter (i.e., heterotrophic respiration ~~[, Rh])~~ ; Bonan, 2008; ~~Chapin~~  
236 ~~et al., 2006; Schulze, 2006).~~ The difference between GPP and Ra ~~is expressed as~~ expresses the net primary  
237 production (NPP) and is the net carbon uptake ~~of~~ by plants that can be used for new biomass production.  
238 Measurements from a range of ecosystems have shown that total plant respiration can be as ~~much~~ large as  
239 50-% of GPP (~~Ryan, 1991~~ e.g., Etzold et al., 2011) and together with Rh comprises total ecosystem  
240 respiration (Re, ~~Re = Ra + Rh~~ Re = Ra + Rh). The partitioning of the ecosystem carbon fluxes can therefore be  
241 summarized as:

$$242 \quad \text{GPP} = \text{NPP} + \text{Ra} = \text{NEP} + \text{Rh} + \text{Ra} \quad (1)$$

245 Earlier campaign-based measurements carried out by Maseyk et al. (2008a) and Grünzweig et al. (2009) in  
246 the semi-arid *Pinus halepensis* (Aleppo pine) Yatir forest indicated that GPP at this site was lower than ~~that~~  
247 among temperate coniferous forests (~~1000–1900~~ 1,000–1,900 g C m<sup>-2</sup> y<sup>-1</sup>) but within the range estimated for  
248 Mediterranean evergreen needle-leaf and boreal coniferous forests (Falge et al., 2002) ~~with; Flechard et al.,~~  
249 2019b), and had a high carbon-use efficiency of 0.4 (CUE = NPP/GPP; DeLucia et al., 2007). The total  
250 flux of CO<sub>2</sub> released from the ecosystem (Re) ~~is~~ can be partitioned into aboveground autotrophic respiration  
251 (i.e., ~~through~~ through foliage and sapwood ~~[, Rf])~~ and soil CO<sub>2</sub> flux (Rs). Rs, in turn, is a combination of three  
252 principal components and can be further partitioned into the components originating from roots or  
253 rhizospheres and mycorrhizas (i.e., belowground autotrophic ~~[, Rsa])~~ and from carbon respired during the  
254 decomposition of dead organic matter by soil microorganisms and macrofaunal (heterotrophic respiration  
255 ~~[, Rh])~~ ; Bahn et al., 2010; Kuzyakov, 2006; ~~Ryan~~ and Law, 2005), ~~and from~~ pedogenic or anthropogenic

256 acidification of soils containing CaCO<sub>3</sub> (Ri; ~~HeinemeyerJoseph~~ et al., ~~2007~~2019; Kuzyakov, 2006), which  
257 is expressed as:

$$258 \quad R_e = R_s + R_f = [R_{sa} + R_h + R_i] + R_f \quad (2)$$

259 Previously published results show that ~~R<sub>s</sub>~~the contribution of R<sub>sa</sub> and R<sub>h</sub> to R<sub>s</sub> ranges from 24–to 65-%%  
260 and from 29 to 74%, respectively, in forest soils in different biomes and ecosystems (~~Andersen et al., 2005;~~  
261 ~~Binkley et al., 2006; Chen et al., 2010; Flechard et al., 2019a; Frey et al., 2006; Johnsen et al., 2007;~~  
262 ~~Hogberg et al., 2009; Olsson et al., 2005; Subke et al., 2011).~~ Some studies reported significant proportions  
263 of abiotic contribution to R<sub>s</sub>, ranging between 10 and 60% (Martí-Roura et al., 2019; Ramnarine et al.,  
264 2012; Joseph et al., 2019). However, most of these experiments were performed in boreal, temperate, or  
265 subtropical forests, and there is a general lack of information on water-limited environments, such as dry  
266 Mediterranean ecosystems. Using both <sup>13</sup>C and CO<sub>2</sub>/O<sub>2</sub> ratios also showed that abiotic processes, such as  
267 CO<sub>2</sub> storage, transport, and interactions with sediments, can influence R<sub>s</sub> measurements at such sites  
268 (Angert et al., 2015; Carmi et al., 2013). Furthermore, root-respired CO<sub>2</sub> can also be dissolved in the xylem  
269 water and carried upward with the transpiration stream (Etzold et al., 2013).

~~The link between soil CO<sub>2</sub> efflux and respiration is complex. For example, a considerable fraction of the  
271 respired CO<sub>2</sub> can be dissolved in soil water, transported in hydrological systems, or take part in reactions  
272 of carbonate systems. In a calcareous soil with a pH of ~8, most system carbon is bicarbonate (HCO<sub>3</sub><sup>-</sup>),  
273 while in calcareous soils, CO<sub>2</sub> can be consumed during calcium carbonate dissolution reactions or released  
274 during reverse reactions as carbonate precipitation (Benavente et al., 2010; Cuezva et al., 2011; Kowalski  
275 et al., 2008). Processes within root CO<sub>2</sub> can be dissolved in xylem water and carried upward through the  
276 transpiration stream (Aubrey and Teskey, 2009; Bloemen et al., 2014).~~

~~Soil carbon in semi-arid regions may be strongly influenced by soil inorganic carbon (SIC; Schlesinger,  
278 1982). Its dissolution (which creates a sink for atmospheric CO<sub>2</sub>) deposition (i.e., source), or recycling can  
279 contribute to soil CO<sub>2</sub> fluxes. On annual to decadal time scales, this contribution is assumed to be marginal  
280 at 3–4 g C m<sup>-2</sup> y<sup>-1</sup>, compared to 60 ± 6 g C m<sup>-2</sup> y<sup>-1</sup> for tundra and up to 1260 ± 57 g C m<sup>-2</sup> y<sup>-1</sup> for tropical  
281 moist forests (Raich and Schlesinger, 1992). This small abiotic flux can be accepted as an insignificant  
282 source compared to biotic CO<sub>2</sub> sources. However, uncertainties concerning the significance of the abiotic  
283 process for C budgets in dry ecosystems with calcareous soils exist.~~

~~Rates of R<sub>s</sub> have been altered due~~Rates of the soil-atmosphere CO<sub>2</sub> flux (R<sub>s</sub>) have been altered owing to  
284 global climatic change, particularly through changes in soil temperature (T<sub>s</sub>) and soil moisture (SWC;  
285 Bond-Lamberty and Thomson, 2010; Buchmann, 2000; Carvalhais et al., 2014; ~~Davidson~~Hagedorn et al.,  
286

287 ~~1998~~2016; Zhou et al., 2009), which could account for 65–92% of the variability of Rs in a mixed  
288 deciduous forest (Peterjohn et al., 1994). Soil moisture impacts on Rs have been observed in arid and  
289 Mediterranean ecosystems, where Ts and SWC are negatively correlated (e.g., Grünzweig et al., 2009).  
290 CO<sub>2</sub> efflux generally increases with increasing soil temperatures (Frank et al., 2002) ~~and~~, which can  
291 produce positive feedback ~~for~~on climate warming (Conant et al., 1998), converting ~~at~~he biosphere from a  
292 net carbon sink to a carbon source (IPCC-AR5 2014). A range of empirical models have been developed to  
293 relate Rs rate and temperature (Balogh et al., 2011; Lellei-Kovács et al., 2011), and the most widely used  
294 ~~model relies~~models rely on the Q<sub>10</sub> approach (Bond-Lamberty and Thomson, 2010), which quantifies the  
295 sensitivity of Rs to temperature and ~~integrates~~can integrate it with physical processes, such as the rate of  
296 O<sub>2</sub> diffusion into and CO<sub>2</sub> diffusion out of soils and the intrinsic temperature dependency of enzymatic  
297 processes (Davidson and Janssens, 2006). Soil moisture (SWC) may be of greater importance than  
298 temperature in influencing Rs in water-limited ecosystems (~~Cable~~Hagedorn et al., ~~2011~~2016; Grünzweig et  
299 al., 2009; Shen et al., 2008; ~~Saleska et al., 1999~~). In general, the Rs rate increases with the increase of SWC  
300 at low levels but decreases at high levels of SWC (Deng et al., 2012; Hui and Luo, 2004; Jiang et al., 2013).  
301 Several studies ~~have connected~~highlight the sensitivity of carbon fluxes in semi-arid Mediterranean  
302 ecosystems to the irregular seasonal and interannual distribution of rain events (Poulter et al., 2014; Ross  
303 et al., 2012). While Rs is generally constrained by low SWC during summer months, abrupt and large soil  
304 CO<sub>2</sub> pulses have been observed after rewetting the dry soil (Matteucci et al., ~~2014~~2015).

305 ~~Partitioning ecosystem CO<sub>2</sub> fluxes using stable isotopes has been proposed as a powerful partitioning~~  
306 ~~approach (Ogee et al., 2004; Yakir and Sternberg, 2000). Earlier studies in the semi-arid Yatir forest~~  
307 ~~indicated that using <sup>13</sup>C creates net ecosystem carbon losses in summer, which are driven by soil emission~~  
308 ~~(Maseyk et al., 2008a), and that different sources of soil carbon can be identified (Grünzweig et al., 2007).~~  
309 ~~Using both <sup>13</sup>C and CO<sub>2</sub>/O<sub>2</sub> ratios also showed that abiotic processes, such as CO<sub>2</sub> storage, transport, and~~  
310 ~~interactions with sediments, can influence Rs measurements at this site (Angert et al.,~~  
311 ~~twofold. First, to obtain detail on partitioning of the carbon fluxes in a semi-arid pine forest to help explain~~  
312 ~~the high productivity and carbon use efficiency recently reported for this ecosystem (Qubaja et al., in press),~~  
313 ~~and provide process-based information to assess the carbon sequestration potential of such a semi-arid~~  
314 ~~afforestation system. Second, to combine this 2016 study with the results of a similar one at the same site~~  
315 ~~in 2003 (mean values for 2001–2006; Grünzweig et al., 2007, 2009) to obtain a long-term perspective across~~  
316 ~~13 years on soil respiration and its partitioning. We hypothesized that the high carbon use efficiency of the~~  
317 ~~dry forest ecosystem is associated with high belowground carbon allocation and relatively low~~

318 decomposition rates, and that the long-term trend associated with warming may be suppressed by the dry  
319 conditions.

320 ~~2015; Carmi et al., 2013). The current research provides follow-up measurements to the 2001–2006 study~~  
321 ~~at the same site to identify long-term temporal changes in the soil-atmosphere CO<sub>2</sub> fluxes in this~~  
322 ~~environment. It also extends the earlier studies by using continuous soil and ecosystem flux measurements~~  
323 ~~and auxiliary analyses to fully and quantitatively partition soil CO<sub>2</sub> to better understand the high-carbon~~  
324 ~~sequestration potential in this semi-arid forest plantation, and.~~

## 325 2. Materials and methods

### 326 2.1. Site description

327 The Yatir forest (3°20'31"20'49" N, 35°03'; 35°03'07" E, 650 m a.s.l.) is ~~located~~situated in the transition  
328 zone between sub-humid and arid Mediterranean climates (Fig. S4SI-1) on the edge of the Hebron mountain  
329 ridge ~~at a mean altitude of 650 m~~. The ecosystem is a semi-arid pine afforestation established in the 1960s  
330 and covering approximately 18 km<sup>2</sup>. The average air temperatures for January and July are 10.0 °C and 25.8  
331 °C, respectively. Mean annual potential evapotranspiration (ET) is 1,600 mm, and mean annual  
332 precipitation is 287 mm. Only winter (December to March) precipitation occurs in this region, creating a  
333 distinctive wet season, while summer (June to October) is an extended dry season. There are short transition  
334 periods between seasons, with a wetting season (i.e., autumn) and a drying season (i.e., spring). The forest  
335 is dominated by Aleppo pine (*Pinus halepensis*; Mill.), with smaller proportions of other pine species and  
336 cypress and little understory vegetation. Tree density in 2007 was 300 trees ha<sup>-1</sup>; mean tree height was 10.0  
337 m; ~~and~~diameter at breast height (DBH) was ~15.9 cm; and the leaf area index (LAI) was ~1.5. The native  
338 background vegetation was sparse shrubland ~~with,~~ which is dominated by the dwarf shrub *Sarcopoterium*  
339 *spinosum* (L.) Spach, with patches of herbaceous annuals and perennials reaching a total vegetation height  
340 of 0.30–0.50 m (Grünzweig et al., 2003, 2007). The root density range is 30–80 roots m<sup>-2</sup> at the upper 0.1  
341 m soil depth, falling to the minimum value (~0 roots m<sup>-2</sup>) at 0.7 m soil depth (Preisler et al., 2019).  
342 Biological soil crust (BSC) is evident in the forest but is less than in the surrounding shrub by ~40%  
343 (Gelfand et al., 2012).

344 The soil at the research site is shallow (20–40 cm) ~~Aeolian~~, reaching only 0.7–1.0 m; the stoniness fraction  
345 for the soil depth (0–1.2 m) is 15–60%, and the rock cover of the surface ranges between 9 and 37%, as  
346 recently described in detail (Preisler et al., 2019); the soil is eolian-origin loess with a clay-loam texture

347 (31% sand, 41% silt, and 28% clay; density:  $1.65 \pm 0.14 \text{ g cm}^{-3}$ ) overlying chalk and limestone bedrock.  
 348 Deeper soils (up to 1.5 m) are sporadically located at topographic hollows. While the natural rocky hill  
 349 slopes in the region are known to create flash floods, the forested plantation reduces runoff dramatically to  
 350 less than 5% of annual rainfall (Shachnovich et al., 2008). Groundwater is deep ( $>300 \text{ m}$ ), reducing the  
 351 possibility of groundwater recharge due to negative hydraulic conductivity or of water uptake by trees from  
 352 the groundwater.

## 353 2.2. Flux and meteorological measurements

354 An instrumented eddy covariance tower was erected in the geographical center of Yatir forest, following  
 355 the EUROFLUX methodology (Aubinet et al., 2000). The system uses a three-dimensional (3D) sonic  
 356 anemometer (Omnidirectional R3, Gill Instruments, Lymington, UK) and a closed path LI-COR 7000  
 357  $\text{CO}_2/\text{H}_2\text{O}$  gas analyzer (LI-COR Inc., Nebraska Lincoln, NE, USA) to measure the evapotranspiration flux  
 358 (ET) and net  $\text{CO}_2$  flux (NEE). EC flux measurements were used to estimate the annual scale of NEP by  
 359 integrating half-hour NEE values. ~~The 15-year NEE record was obtained after long-term operation of our~~  
 360 ~~EC measurement site (since 2000; see Rotenberg and Yakir, 2010) provides continuous flux and~~  
 361 ~~meteorological data with about 80% coverage, which are subjected to~~  $U^*$  night-time correction, ~~gap filling,~~  
 362 and quality control, ~~and gap filling is based on the extent of the missing data.~~ as recently described in more  
 363 detail in Tatarinov et al. (2016). A site-specific algorithm was used for flux partitioning into  $R_e$  and GPP.  
 364 Daytime ecosystem respiration ( $R_{e-d}$ , in  $\mu\text{mol m}^{-2} \text{ s}^{-1}$ ) was estimated based on measured night-time ~~values~~  
 365 ~~( $R_{e-n}$ ; i.e., when the global radiation was  $<5 \text{ W m}^{-2}$ ) values ( $R_{e-n}$ ), averaged for the first three half-hours~~  
 366 of each night. The daytime respiration for each half-hour was calculated according to Eq. 3 (Maseyk et al.,  
 367 2008a; Tatarinov et al., 2016):

$$368 \quad R_{e-d} = R_{e-n}(\alpha_1 \beta_s^{dT_s} + \alpha_2 \beta_w^{dT_a} + \alpha_3 \beta_f^{dT_a}) \quad (3)$$

369  
 370 where  $\beta_s$ ,  $\beta_w$ , and  $\beta_f$  are coefficients that correspond to soil, wood, and foliage, respectively;  $dT_s$  and  $dT_a$   
 371 are soil and air temperature deviations from the values at the beginning of the night; and  $\alpha_1$ ,  $\alpha_2$ , and  $\alpha_3$  are  
 372 partitioning coefficients fixed at 0.5, 0.1, and 0.4, respectively. The  $\beta_s$ ,  $\beta_w$ , and  $\beta_f$  coefficients were  
 373 calculated as follows:  $\beta_s$  ~~= values were based on  $Q_{10}$  from the Grünzweig et al. (2009) study at the same~~  
 374 ~~site; where  $\beta_s = 2.45$  for wet soil (i.e., soil water content SWC in the upper 30 cm above 20% vol);  $\beta_s =$~~   
 375 ~~1.18 for dry soil (i.e., based on  $Q_{10}$  from the Grünzweig et al. [2009] study at the same site SWC in the upper~~  
 376 ~~30 cm equal to or below 20% vol);  $\beta_f = 3.15 - 0.036 T_a$ ; and  $\beta_w = 1.34 + 0.46 \exp(-0.5((D_o Y -$~~

377 162)/66.1)<sup>2</sup>), where DoY is the day of the hydrological year starting from 1 October~~first~~. Finally, GPP was  
378 calculated as  $GPP = NEE - R_e$ . Negative values of the NEE and GPP indicated that the ecosystem was a  
379 CO<sub>2</sub> sink.

380 Half-hour auxiliary measurements used in this study included photosynthetic activity radiation (PAR mol  
381 m<sup>-2</sup> s<sup>-1</sup>), vapor pressure deficit (VPD, kPa), wind speed (m s<sup>-1</sup>), and relative humidity (RH, %)~~—%), with~~  
382 additional measurements ~~areas~~ described elsewhere (Tatarinov et al., 2016). ~~Air~~Furthermore, the soil  
383 microclimatology half-hour measurements were measured and calculated with soil chamber measurements,  
384 using the LI-8150-203 (LI-COR, Lincoln, NE), as described below, namely air temperature (Ta, °C)~~) and~~  
385 relative humidity (RH, %), ~~and soil temperature (Ts, °C) were also measured and calculated using soil~~  
386 ~~chambers %) at 20 cm above the soil surface and soil temperature (Ts, °C) at a 5 cm soil depth. These were~~  
387 ~~located at 21 points and measured every half hour using soil chamber system (LI8150-203, LI COR~~  
388 ~~Lincoln, NE). Volumetric soil temperature probe, as well as volumetric~~ soil water content (SWC<sub>0-10</sub>) ~~was~~  
389 ~~measured, m<sup>3</sup> m<sup>-3</sup>) in the upper 10 cm of the soil very half hour near the chambers, using the ThetaProbe~~  
390 model ML2x (Delta-T Devices Ltd., Cambridge, UK)~~), which was~~ calibrated to the soil composition based  
391 on the manufacturer's equations.

### 392 **2.3. Soil CO<sub>2</sub> fluxes**

393 Soil CO<sub>2</sub> fluxes (Rs) ~~was~~were measured ~~using~~with automated non-steady-state systems, using 20 cm  
394 diameter opaque chambers, and a multiplexer to allow for simultaneous control of several chambers (LI -  
395 8150, -8100-101, -8100-104; LI-COR, Lincoln, NE). ~~Precision~~The precision of CO<sub>2</sub> measurements in  
396 ~~chamber~~the chambers' air ~~was~~is ±1.5-% of the ~~measurements~~measurements' range (0–20,000 ppm). The  
397 ~~chamber~~chambers were closed ~~on~~on preinstalled PVC collars 20 cm ~~in~~ diameter, ~~inserted 5 cm into the~~  
398 ~~soil and 6 cm above the surface,~~ allowing for short measurement time (i.e., 2 min). ~~When~~  
399 ~~measurements were not being taken, chambers were), and~~ positioned away from the collars. ~~for the rest of~~  
400 the time. Data were collected using a system in which air from the ~~chamber~~chambers was circulated (2.5 l  
401 min<sup>-1</sup>) through an infrared gas analyzer (IRGA) to record CO<sub>2</sub> (μmol CO<sub>2</sub>/mol air) and H<sub>2</sub>O (mmol H<sub>2</sub>O/mol  
402 air) concentrations in the system logger (1 s<sup>-1</sup>). Gap filling of missing data due to technical problems (i.e.,  
403 27 % of the data across the study period between November 2015 and October 2016) was based on the  
404 average diurnal cycle of each month.

405 The rates of soil CO<sub>2</sub> flux~~es~~, Rs (μmol CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup>), were calculated from chamber data using a linear fit  
406 of change in ~~the~~ water-corrected CO<sub>2</sub> mole fraction ~~and~~using Eq. 4 (LiCor Manual, 2015) as follows:

407 
$$R_s = \frac{dC}{dt} \cdot \frac{vP}{sT_aR} \quad (4)$$

408 where  $dC/dt$  is the rate of change in the water-corrected  $CO_2$  mole fraction ( $\mu\text{mol } CO_2 \text{ mol}^{-1} \text{ air s}^{-1}$ ),  $v$  is the  
 409 system volume ( $\text{m}^3$ ),  $P$  is the chamber pressure (Pa),  $s$  is the soil surface area within the collar ( $\text{m}^2$ ),  $T_a$  is  
 410 the chamber air temperature (K), and  $R$  is the gas constant ( $\text{J mol}^{-1} \text{ K}^{-1}$ ). A measurement period of 2 minutes  
 411 was used, based on preliminary tests to obtain the most linear increase of  $CO_2$  in the chambers with the  
 412 highest  $R^2$ .

413 Soil  $CO_2$  fluxes in the experimental plot were measured between November 2015 and October 2016 with  
 414 means of three measurement chambers using 21 collars arranged grouped in seven groups (sites) in the forest  
 415 stand, with three locations (i.e., three collars) per site, based on different distances from the nearest tree  
 416 (Dt). The collars were inserted 5 cm into the soil. Data were recorded on a half-hour basis (48 daily records).  
 417 The three chambers were rotated between the seven sites every 1–2 weeks to cover all sites and to assess  
 418 spatial and temporal variations.

419 Upscaling of the collar measurements to plot-scale soil  $CO_2$  flux was carried out by grouping collars based  
 420 on ~~the distance from trees (Dt)~~ three locations (i.e., under trees [ $<-1$  m from nearest tree; UT], in gaps  
 421 between trees [ $1-2.3$  m; BT], and in open areas [ $>-2.3$  m; OA]). ~~One~~, with one chamber ~~was~~  
 422 ~~measured taking measurements~~ at each microsite group to estimate location, and estimating the fractional  
 423 areas ( $\emptyset$ ) of the three locations based on mapping the sites according to the distances noted above, ~~which~~  
 424 ~~was~~ previously done (by Raz-Yaseef et al., (2010):

425 
$$R_s = R_{sOA} * \emptyset_{OA} + R_{sBT} * \emptyset_{BT} + R_{sUT} * \emptyset_{UT} \quad (5)$$

426 
$$\emptyset_{OA} + \emptyset_{BT} + \emptyset_{UT} = 1 \quad (6)$$

427 The annual scale of  $R_s$  was derived from the up-scaled upscaled chamber measurements (Eq. 5) based on  
 428 daily records (48 half-hourly values) of spatial up-scaled upscaled  $R_s$ . ~~Gap filling of missing data due to~~  
 429 ~~technical problems (i.e., 27% of the data across the study period of 2015–2016) was based on the average~~  
 430 ~~diurnal cycle of each month, and such data were averaged to obtain the estimate of the annual scale of  $R_s$ .~~

431  
 432 Estimating the temperature sensitivity of  $R_s$  ( $Q_{10}$ ) was ~~done performed~~ as described by Davidson and  
 433 Janssens (2006) using a first-order exponential equation (see also Xu et al., 2015);):

434 
$$R_s = ae^{bT_s} \quad (7)$$

435 where  $R_s$  represents the half-hour spatial up-scaled upscaled time series of soil respiration flux ( $\mu\text{mol m}^{-2}$   
 436  $\text{s}^{-1}$ ),  $T_s$  ( $^{\circ}\text{C}$ ) is soil temperature at a 5 cm depth (up-scaled upscaled spatially and temporally using the same

437 method as for Rs), and a and b are fitted parameters. The b values were used to calculate the Q<sub>10</sub> value  
438 according to the following equation:

$$439 \quad Q_{10} = e^{10b} \quad (8)$$

#### 440 **2.4. Soil CO<sub>2</sub> flux partitioning**

441 Determination of different sources of soil CO<sub>2</sub> efflux was based on linear mixing models (Lin et al., 1999)  
442 to estimate proportions for three main sources (autotrophic, heterotrophic, and abiotic), using isotopic  
443 analysis of soil CO<sub>2</sub> profiles and soil incubation data from eight campaigns (January to September) during  
444 2016, according to Equations 9–11. Partitioning of the monthly Rs values into components was done using  
445 a 3-endmember triangular model for interpreting the δ<sup>13</sup>C and Δ<sup>14</sup>C values of CO<sub>2</sub> flux; the 3-endmember  
446 triangular corners are the autotrophic (R<sub>sa</sub>), heterotrophic (R<sub>h</sub>), and abiotic (R<sub>i</sub>) sources of Rs. The δ<sup>13</sup>C  
447 and Δ<sup>14</sup>C isotope signatures of monthly Rs ~~are located~~locate it inside the triangle (Fig. ~~S2~~SI-2):

$$448 \quad \delta^{13}C_{Rs} = f_{sa} * \delta^{13}C_{sa} + f_h * \delta^{13}C_h + f_i * \delta^{13}C_i \quad (9)$$

$$449 \quad \Delta^{14}C_{Rs} = f_{sa} * \Delta^{14}C_{sa} + f_h * \Delta^{14}C_h + f_i * \Delta^{14}C_i \quad (10)$$

$$450 \quad 1 = f_{sa} + f_h + f_i \quad (11)$$

451  
452 ~~Here, where~~ f indicates the fraction of total soil flux (e.g., ~~f<sub>h</sub> = R<sub>h</sub>/R<sub>s</sub>~~), while subscripts sa, h, and i indicate  
453 autotrophic, heterotrophic, and inorganic components, respectively. The three ~~equation systems were~~  
454 equations system was used to solve the three unknown f fractions of the total soil flux based on empirical  
455 estimates of the isotopic ~~end members~~endmembers. Additionally, δ<sup>13</sup>C and Δ<sup>14</sup>C are the stable and  
456 radioactive carbon isotopic ratios, where δ<sup>13</sup>C = [(<sup>13</sup>C/<sup>12</sup>C)<sub>sample</sub>/<sup>13</sup>C/<sup>12</sup>C<sub>reference</sub>]-1]\*1000‰ and the  
457 reference is the Vienna international standard (VPDB). Radiocarbon data are expressed as Δ<sup>14</sup>C in parts per  
458 thousand or per mil (‰), which is the deviation of a sample <sup>14</sup>C/<sup>12</sup>C ratio relative to the OxI standard in  
459 1950 (see Taylor et al., 2015), that is, Δ<sup>14</sup>C = [(<sup>14</sup>C/<sup>12</sup>C)<sub>sample</sub>/(0.95\*<sup>14</sup>C/<sup>12</sup>C<sub>reference</sub>\*exp[(y-1950)/8267])-  
460 1]\*1000‰, where y is the year of sample ~~measurement~~measurements.

461 The δ<sup>13</sup>C<sub>Rs</sub> was estimated monthly using the Keeling plot approach (Figs. ~~S3~~SI-3 and 4; Pataki et al., 2003;  
462 Taneva and Gonzalez-Meler, 2011). Soil air was sampled using closed-end stainless steel tubes (6 mm  
463 diameter) perforated near the tube bottom at four depths (30, 60, 90, and 120 cm). Samples of soil air were  
464 collected in pre-evacuated 150 mL glass flasks with high-vacuum valves, ~~with~~ the dead volume in the tubing  
465 and flask necks having been purged with soil air using a plastic syringe equipped with a three-way valve.

466 Note that the Keeling plot approach is based on the 2-endmembers mixing model (see Review of Pataki et  
467 al., 2003), which often does not hold in soils because of variations in the  $\delta^{13}\text{C}$  values of source material  
468 with depth (see a recent example in Joseph et al., 2019). However, probably because of the very dry  
469 conditions at our study site, no change in  $\delta^{13}\text{C}$  with depth in the root zone is observed ( $\pm 0.1\%$  across the  
470 35 cm depth profiles; Fig. SI-5), providing an opportunity to avoid this caveat. The soil  $\text{CO}_2$  samplings  
471 carried out therefore represented predominantly the mixing of atmospheric  $\text{CO}_2$  with a single integrated soil  
472 source signal, consistent with the Keeling plot approach.

473 The autotrophic ( $\delta^{13}\text{C}_{\text{sa}}$ ) endmember was estimated based on incubations during the sampling periods of  
474 excised roots, following Carbone et al. (2008). Fine roots (<2 mm diameter) were collected, rinsed with  
475 deionized water, and incubated for 3 hours in 10 mL glass flasks connected ~~through~~with Swagelok Ultra-  
476 Torr tee fittings to 330 mL glass flasks equipped with Louwers high-vacuum-valves. The flasks were  
477 flushed with  $\text{CO}_2$ -free air at room temperature close to field conditions. The  $\text{CO}_2$  was allowed to accumulate  
478 to at least ~~2000~~2,000 ppm (~2 h).

479 The heterotrophic ( $\delta^{13}\text{C}_{\text{h}}$ ) endmember was estimated as in Taylor et al. (2015), and similar to the root-  
480 incubation experiment, soil samples from the top 5 cm of the litter layer or 10 cm below the soil surface  
481 were collected, and roots were carefully removed to isolate heterotrophic components. Root-free soils were  
482 placed in 10 mL glass flasks and allowed to incubate for 24 hours before being transferred to evacuated  
483 330 mL glass flasks. The inorganic source ( $\delta^{13}\text{C}_{\text{i}}$ ) endmember was estimated using one gram of dry soil  
484 (ground to pass through a 0.5 mm mesh) placed in a 10 mL tube with a septum cap; then, 12 mL of 1M HCl  
485 was added to dissolve the carbonate fraction, and the fumigated  $\text{CO}_2$  withdrawn from each tube was  
486 collected using a 10 mL syringe and injected into a 330- mL evacuated flask for isotopic analysis.

487 Radiocarbon estimates were based on the work of Carmi et al. (2013) at the same site, adjusted to the  
488 measured atmospheric  $^{14}\text{C}$  values during the study period (49.5-‰; Carmi et al., 2013). The  $\Delta^{14}\text{C}_{\text{sa}}$  and  
489  $\Delta^{14}\text{C}_{\text{h}}$  endmembers were estimated based on the assumption that they carry the  $^{14}\text{C}$  signatures of 4 and 8.5  
490 years, respectively, older than the  $^{14}\text{C}$  signature of the atmosphere at the time of sampling, based on mean  
491 ages previously estimated (Graven et al., 2012; Levin et al., 2010; Taylor et al., 2015).  $\Delta^{14}\text{C}_{\text{i}}$  was obtained  
492 from Carmi et al. (2013; Table 2). Monthly values of  $\Delta^{14}\text{C}_{\text{Rs}}$  were obtained using the linear equation of the  
493 regression line of the measured  $\delta^{13}\text{C}$  values of  $\text{R}_{\text{sa}}$ ,  $\text{R}_{\text{sh}}$ , and  $\text{R}_{\text{i}}$  and the corresponding estimated  $\Delta^{14}\text{C}$   
494 values (Fig. S2SI-2) and monthly  $\delta^{13}\text{C}$  values of  $\text{R}_{\text{s}}$ .

## 495 2.5. Isotopic analysis

496 Isotopic analysis followed the methodology described in Hemming et al. (2005). The  $\delta^{13}\text{C}$  of  $\text{CO}_2$  in the air  
497 was analyzed using a continuous flow mass spectrometer connected to a 15-flask automatic manifold  
498 system. An aliquot of 1.5 mL of air was expanded from each flask into a sampling loop on a 15-position  
499 valve (Valco Houston, TX, USA).  $\text{CO}_2$  was cryogenically trapped from the air samples using helium as a  
500 carrier gas; it was then separated from  $\text{N}_2\text{O}$  with a Carbosieve G (~~Sigmaaldrich~~Sigma Aldrich) packed  
501 column at  $70^\circ\text{C}$  and analyzed on a Europa 20-20 Isotope Ratio Mass Spectrometer (Crewe, UK).  $\delta^{13}\text{C}$   
502 results were quoted in parts per thousand (‰) relative to the VPDB international standard. The analytical  
503 precision was 0.1-‰. To measure  $[\text{CO}_2]$ , an additional 40.0 mL ~~sub-sample~~subsample of air from each  
504 flask was expanded into mechanical bellows and then passed through an infrared gas analyzer (LICOR  
505 6262; Lincoln, NE, USA) in an automated system. The precision of these measurements was 0.1 ppm.  
506 Flasks filled with calibrated standard air were measured with each batch of 10 sample flasks; five standards  
507 were measured per 10 samples for  $\delta^{13}\text{C}$  analyses and four standards per 10 samples for  $[\text{CO}_2]$  analyses.

508 Organic matter samples were dried at  $60^\circ\text{C}$  and milled using a Wiley Mill fitted with size 40 mesh, and soil  
509 samples were ground in a pestle and mortar. Soils containing carbonates were treated with M1M  
510 hydrochloric acid. Between 0.2 and 0.4 mg of each dry sample ~~were~~was weighed into tin capsules  
511 (Elemental Microanalysis Ltd., Okehampton, UK), and ~~their  $\delta^{13}\text{C}$~~ the  $\delta^{13}\text{C}$  of each was determined using an  
512 elemental analyzer linked to a Micromass Optima IRMS (Manchester, UK). Three replicates of each sample  
513 were analyzed, and two samples of a laboratory working standard cellulose were measured for every 12  
514 samples. Four samples of the acetanilide (Elemental Microanalysis Ltd.) international standard were used  
515 to calibrate each run, and a correction was applied to account for the influence of a blank cup. The precision  
516 was 0.1‰.

## 517 **2.6. Total ~~below-ground~~belowground carbon allocation (TBCA)**

518 TBCA ( $\text{g C m}^{-2} \text{ y}^{-1}$ ) was calculated following Giardina and Ryan (2002) for the study year (November  
519 2015–October 2016) as follows:

$$520 \quad \text{TBCA} = R_s - R_l + \Delta C_{\text{soil}} \quad (12)$$

521 where  $R_l$  is the annual ~~above-ground~~aboveground litter production ~~from~~between November 2014– and  
522 October 2015, and  $\Delta C_{\text{soil}}$  is the annual change in ~~below-ground~~belowground total soil organic C. Litter  
523 production, not measured during the present study, was estimated based on values obtained by Masyk et al.  
524 (2008b) for 2000–2006 ( $56 \text{ g C m}^{-2} \text{ y}^{-1}$ ) and assumed to have increased in the study period (2014–2015)  
525 proportionally to the measured increase in leaf area index (LAI; 1.31 to 1.9; i.e.,  $R_l = -[(1.9*56)/1.31] = 83$   
526  $\text{g C m}^{-2} \text{ y}^{-1}$ ) ~~and~~. For herbaceous litter production. ~~Three, three~~ plots of  $25 \text{ m}^2$  were randomly selected

527 in 2002 and harvested at the end of the growing season, ~~at which time~~ total fresh biomass was weighed, and  
528 subsamples were used to determine dry weight and C content. Grünzweig et al. (2007) found that  
529 herbaceous litter production was close to the average rainfall for the specific year. ~~This; this~~ method was  
530 adapted in the current study for the period between November 2014 and October 2015. Since ~~above~~  
531 ~~ground~~aboveground litter (RI; the sum of tree litter and herbaceous litter production) of a given year was  
532 mainly produced during that year but decayed during the following hydrological year, TBCA was on the  
533 current year's Rs (2015–2016) and the previous year's RI- (2014–2015).  $\Delta C_{\text{soil}}$  was set ~~to~~ constant as the  
534 average annual ~~below-ground~~belowground carbon increase since afforestation (Qubaja et al., ~~unpublished in~~  
535 press).

## 536 2.6. Statistical analyses

537 Two-way ANOVA tests were performed at a significance level set at  $p = 0.001$  to detect significant effects  
538 of locations (OA, BT, and UT), sites, and their interactions on Rs and meteorological parameters. Pearson  
539 correlation analysis ( $r$ ) was used to detect the correlation between Rs and meteorological parameters. To  
540 quantify spatio-temporal variability in Rs, the coefficient of variation (CV%) was calculated as  
541  $[(\text{STDEV}/\text{Mean}) * 100\%]$ . Heterogeneity was considered weak if  $\text{CV}\% \leq 10\%$ , moderate if  $10\% < \text{CV}\% \leq$   
542  $100\%$ , and strong if  $\text{CV}\% > 100\%$ . All the analyses were performed using Matlab software, Version R2017b  
543 (MathWorks, Inc., MA, USA).

544 ~~To quantify spatial temporal variability in Rs, the coefficient of variation (CV %) was calculated as~~

$$545 \quad \text{CV} = \frac{\text{Standard deviation}}{\text{mean}} \times 100\% \quad (13)$$

546  
547  
548 ~~Heterogeneity was considered weak if  $\text{CV}\% \leq 10\%$ , moderate if  $10\% < \text{CV}\% \leq 100\%$ , and strong if  $\text{CV}\%$   
549  $> 100\%$ . All the analyses were performed using Matlab software, version R2017b (MathWorks, Inc.).~~

## 550 3. Results

### 551 3.1. Spatial variations

552 The spatial variations in Rs across ~~collars~~locations (distance from nearest tree) and ~~microsites~~sites (across  
553 the study area) are reported in Table 1, together with other measured variables. The results indicated an

554 overall mean  $R_s$  value of  $0.8 \pm 0.1 \mu\text{mol m}^{-2} \text{s}^{-1}$ , with distinct values for the three micrositeslocations.  $R_s$   
555 was greater at ~~the~~-UT siteslocations than at the BT and OA siteslocations by a factor of  $\sim 2$ . The spatial  
556 variability among the micrositeslocations was also apparent in the  $R_s$  daily cycle (Fig. 1), with clear  
557 differences between the wet season (November to April), when the UT showed consistently higher  $R_s$   
558 values than at other siteslocations by a factor of about 1.6; and the dry season by a factor of  
559 ~~about~~approximately 2.6. Note that the daily peak in  $R_s$  ~~remains~~remained at ~~mid-day~~midday in both the wet  
560 and dry seasons. Overall, the 21 collars showed moderate variations (CV = 55-%; Table 1), ~~negative~~  
561 ~~correlations between~~ $R_s$  ~~and~~was negatively correlated with distance from trees (Dt;  $r = 0.62$ ;  $p < 0.01$ ) and  
562 with soil and air temperatures (Ts and Ta;  $r = 0.45$ ;  $p < 0.05$ ), and ~~positive correlations between SWC and~~  
563 ~~positively correlated with soil water content and~~ relative humidity (SWC and RH;  $r = 0.50$ ;  $p < 0.05$ ). The  
564 inverse correlation between  $R_s$  and distance from the nearest tree could be useful in considering the  
565 expected decline in stand density due to thinning and mortality (e.g., associated with a drying climate). For  
566 a first approximation, the results indicate that decreasing from the present stand density of 300 trees ha<sup>-1</sup> to  
567 100 trees ha<sup>-1</sup> and the resulting increase in mean distance among trees could result in decreasing ecosystem  
568  $R_s$  by 11%.



570 **Table 1** † Annual mean of half-hour values across sites locations (OA, open area; BT, between trees; UT, under tree) and in seven sites in the forest during the study  
 571 period, of soil respiration flux rates (Rs) together with the soil water content at 10 cm depth (SWC), minimum distances from nearby tree (Dt), soil temperature at  
 572 5 cm depth (Ts), and air temperature (Ta) and relative humidity (RH) at the soil surface; (numbers in parenthesis indicate  $\pm$ se).

<u>Locations</u>	<u>Sites</u>	<u>Sites</u>	<u>Points</u>	<b>Rs</b>	<b>SWC</b>	<b>Dt</b>	<b>Ts</b>	<b>Ta</b>	<b>RH</b>
				[ $\mu\text{mol m}^{-2} \text{s}^{-1}$ ]	[ $\times 100 \text{ m}^3 \text{ m}^{-3}$ ]	[m]	[ $^{\circ}\text{C}$ ]	[ $^{\circ}\text{C}$ ]	[%]
OA	1			1.64 (0.02)	16.5 (0.2)	2.9	15.6 (0.1)	15.4 (0.2)	59.7 (0.5)
	2			0.72 (0.01)	14.5 (0.2)	3.6	15.9 (0.2)	15.0 (0.2)	58.4 (0.6)
	3			1.23 (0.02)	19.3 (0.2)	7.0	20.6 (0.3)	18.2 (0.2)	53.5 (0.5)
	4			0.38 (0.01)	11.3 (0.2)	3.0	22.6 (0.2)	20.8 (0.1)	58.9 (0.4)
	5			0.38 (0.01)	5.8 (0.2)	3.0	25.5 (0.1)	24.0 (0.1)	43.1 (0.4)
	6			0.31 (0.01)	5.7 (0.4)	2.8	30.0 (0.3)	26.2 (0.3)	51.8 (0.9)
	7			0.14 (0.01)	6.1 (0.3)	3.5	25.5 (0.2)	23.2 (0.3)	44.5 (0.9)
		<b>Average</b>			<b>0.68 (0.21)</b>	<b>11 (0)</b>	<b>3.7 (0.6)</b>	<b>22.3 (2.0)</b>	<b>20.4 (1.6)</b>
	<b>CV [%]</b>			<b>81 %</b>	<b>50%</b>	<b>41%</b>			<b>13 %</b>
BT	1			0.77 (0.01)	10.5 (0.2)	1.8	16.1 (0.1)	15.2 (0.2)	60.5 (0.5)
	2			0.88 (0.01)	12.1 (0.2)	1.5	14.8 (0.2)	14.7 (0.2)	59.5 (0.6)
	3			0.84 (0.01)	20.4 (0.2)	2.7	20.1 (0.3)	18.4 (0.2)	54.1 (0.6)
	4			0.91 (0.01)	14.4 (0.2)	2.7	23.3 (0.2)	21.3 (0.2)	58.5 (0.4)
	5			0.41 (0.00)	3.9 (0.2)	2.0	24.6 (0.1)	24.0 (0.1)	43.2 (0.4)
	6			0.41 (0.01)	3.3 (0.4)	2.5	29.1 (0.2)	26.0 (0.3)	52.5 (0.8)
	7			0.46 (0.01)	5.5 (0.3)	1.2	23.9 (0.1)	22.8 (0.3)	45.7 (0.9)
		<b>Average</b>			<b>0.67 (0.09)</b>	<b>10 (0)</b>	<b>2.0 (0.2)</b>	<b>21.7 (1.9)</b>	<b>20.3 (1.6)</b>
	<b>CV [%]</b>			<b>35 %</b>	<b>63%</b>	<b>29%</b>			<b>13 %</b>
UT	1			1.22 (0.02)	9.3 (0.2)	0.2	15.7 (0.1)	15.2 (0.2)	60.0 (0.5)
	2			1.42 (0.01)	14.0 (0.2)	0.3	14.8 (0.2)	14.8 (0.2)	59.4 (0.6)
	3			1.64 (0.01)	19.8 (0.2)	0.5	19.0 (0.2)	18.0 (0.2)	54.5 (0.6)
	4			1.90 (0.02)	11.3 (0.2)	0.6	22.0 (0.1)	20.8 (0.1)	59.0 (0.4)
	5			1.16 (0.01)	4.0 (0.2)	0.4	23.9 (0.1)	23.7 (0.1)	44.1 (0.4)
	6			1.29 (0.01)	4.5 (0.4)	0.2	29.5 (0.3)	25.9 (0.3)	52.7 (0.9)
	7			0.89 (0.01)	5.2 (0.3)	0.2	25.0 (0.1)	23.0 (0.3)	45.5 (0.9)
		<b>Average</b>			<b>1.36 (0.13)</b>	<b>10 (0)</b>	<b>0.3 (0.1)</b>	<b>21.4 (2.0)</b>	<b>20.2 (1.6)</b>
	<b>CV [%]</b>			<b>25 %</b>	<b>60%</b>	<b>46%</b>			<b>12 %</b>
All	<b>Average (SE)</b>			<b>0.8 (0.1)</b>	<b>11 (0)</b>	<b>2.0 (0.4)</b>	<b>21.8 (1.1)</b>	<b>20.3 (0.9)</b>	<b>53.3 (1.4)</b>
	<b>Max</b>			<b>1.90</b>	<b>20</b>	<b>7.0</b>	<b>30.0</b>	<b>26.2</b>	<b>60.5</b>

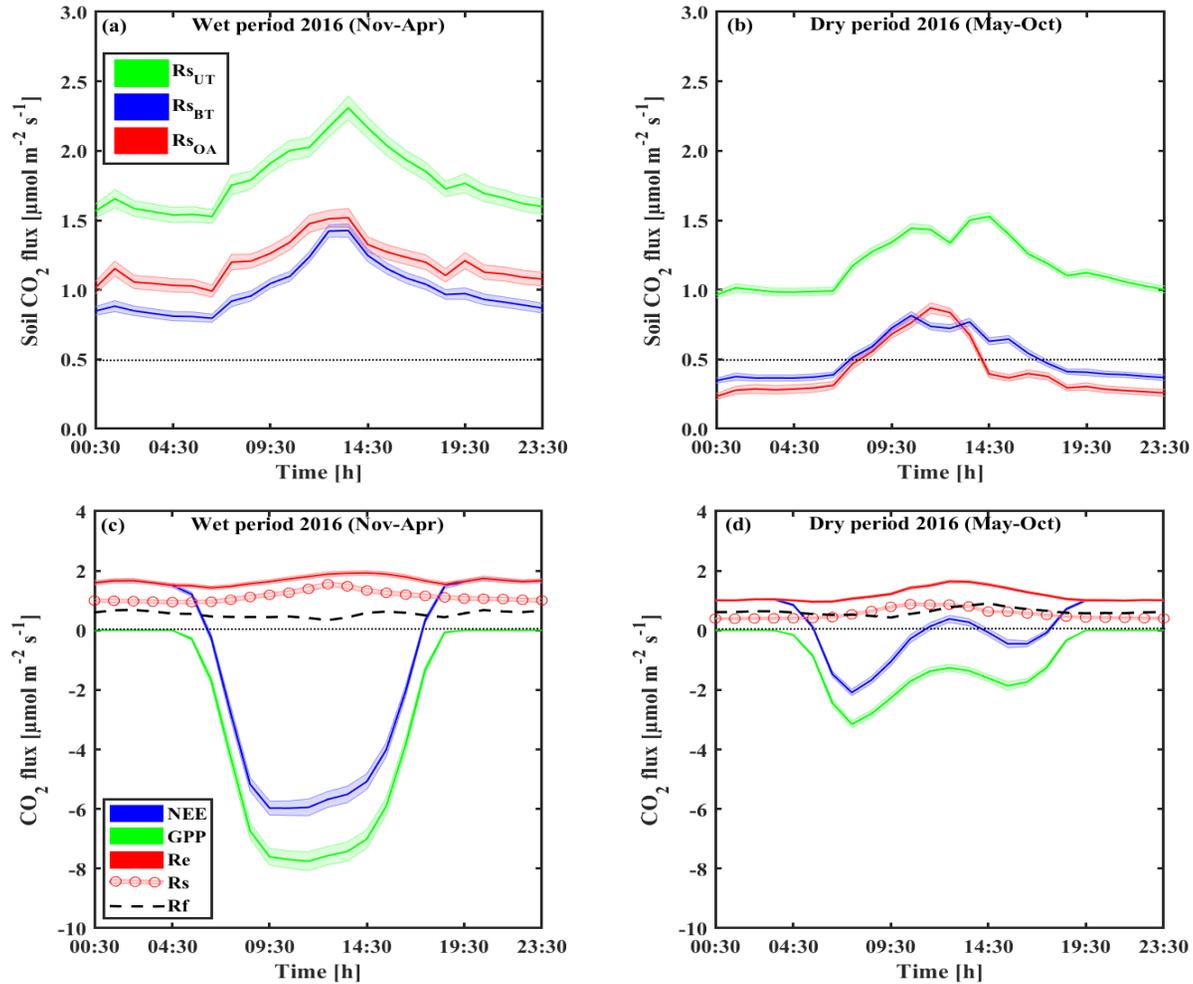
	<b>Min</b>	<b>0.14</b>	<b>3</b>	<b>0.2</b>	<b>14.8</b>	<b>14.7</b>	<b>43.1</b>
	<b>CV [%]</b>	<b>55 %</b>	<b>55%</b>	<b>82%</b>			<b>12 %</b>
<b><u>Two-way</u></b>	<b><u>Site</u></b>	<b><u>0.000</u></b>	<b><u>0.000</u></b>		<b><u>0.000</u></b>	<b><u>0.000</u></b>	<b><u>0.000</u></b>
<b><u>ANOVA</u></b>	<b><u>Location</u></b>	<b><u>0.000</u></b>	<b><u>0.000</u></b>		<b><u>0.000</u></b>	<b><u>0.220</u></b>	<b><u>0.074</u></b>
<b><u>(P value)</u></b>	<b><u>Site x Location</u></b>	<b><u>0.000</u></b>	<b><u>0.000</u></b>		<b><u>0.000</u></b>	<b><u>0.645</u></b>	<b><u>0.961</u></b>
<b>Pearson Correlation with Rs</b>			<b>.50*</b>	<b>-.62**</b>	<b>-.45*</b>	<b>-.45*</b>	<b>.50*</b>

573

574

575  
576

\*\* Correlation is significant at the 0.01 level (two-tailed).  
\* Correlation is significant at the 0.05 level (two-tailed).



577  
578  
579

**Figure 1** Representative diurnal cycles of soil respiration ( $R_s$ ; using soil chambers across microsites: open-area, OA; between-trees, BT; under-trees, UT) and sites in panels a and b, and of net ecosystem exchange (NEE; canopy scale eddy covariance) and gross primary production (GPP), and ecosystem respiration

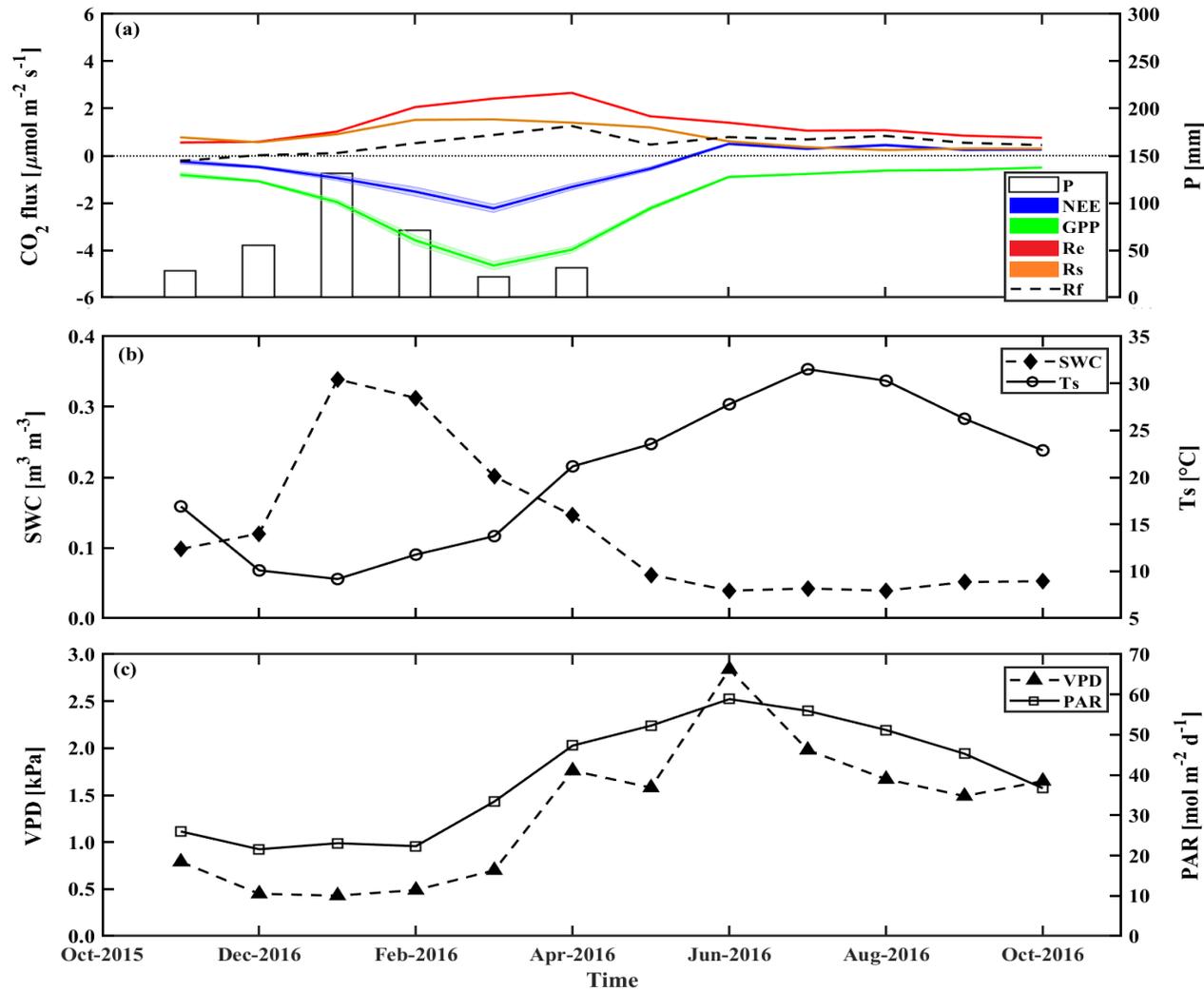
580 (Re) and its partitioning to soil respiration (Rs) and aboveground tree respiration (Rf) in panels c and d, during the wet (Nov–Apr) and dry (May–Oct) periods.  
581 Based on half-hour values over the diurnal cycle; shaded areas indicate  $\pm$ se; Rf was estimated as the residual as  $Rf = Re - Rs$  and was presented as ~~black-a~~ dashed  
582 line.

583

### 584 3.2. Temporal dynamics

585 On the diurnal timescale, CO<sub>2</sub> fluxes showed typical daily cycles (Fig. 1). As expected, on average, all CO<sub>2</sub> fluxes were higher during the wet period  
586 compared to the dry season by a factor of ~2. However, Rs and Re peaked around ~~mid-day~~midday in both the wet and dry seasons, while the more  
587 physiologically controlled NEE and GPP showed a shift from ~~mid-day~~midday (around 11:00–14:00) to early morning (08:00–11:00) in the dry  
588 season, with a ~~mid-day~~midday depression and a secondary afternoon peak (Fig. 1d).

589 The temporal variations across the seasonal cycle are reported in Fig. 2, based on monthly mean values, exhibiting sharp differences between the  
590 wet and dry seasons. As previously observed in this semi-arid site, all CO<sub>2</sub> fluxes peak in early spring between March and April. The corresponding  
591 high-resolution data are reported in Fig. ~~S5 and~~SI-6, which show also that ~~in the~~ high winter (February–) Rs rates were associated with clear days  
592 when photosynthetic active radiation (PAR) increased with air temperature, Ta. These data also show that, following rainy days, daily Rs values  
593 could reach  $6.1 \mu\text{mol m}^{-2} \text{s}^{-1}$ , although the average was  $1.1 \pm 0.2 \mu\text{mol m}^{-2} \text{s}^{-1}$  during the wet period, which diminished by ~55% in the dry season  
594 to mean daily values of  $0.5 \pm 0.1 \mu\text{mol m}^{-2} \text{s}^{-1}$ . In spring (April), all CO<sub>2</sub> fluxes peaked during the crossover trends of decreasing soil moisture  
595 content, and increasing both temperature, and PAR (Fig. ~~S5~~SI-6).



596

597

598

599

600

**Figure 2** Seasonal trends of monthly mean values during the research period of a) the fluxes of net ecosystem exchange (NEE), gross primary production (GPP), and ecosystem respiration (Re) and its components, soil respiration (Rs) and aboveground tree respiration (Rf); and monthly mean of key environmental parameters, b) soil water content at the top 10 cm (SWC<sub>0-10</sub>) and soil temperature at 5 cm (Ts), and c) vapor pressure deficit (VPD) and photosynthetic activity radiation (PAR). Rf is obtained from the Re-Rs.

601  
 602 The temporal variations in the half-hour values of Rs reflected changes in soil moisture at 0–5 cm depth and PAR ( $r = 0.5$  and  $0.2$ , respectively;  $p <$   
 603  $0.01$ ) and negative correlations with Ts and RH ( $r = 0.2$  and  $0.1$ , respectively;  $p < 0.01$ ). The variations in the integrated Rs showed a CV of 71%,  
 604 with the temporal variations dominated strongly by PAR (CV  $> 100\%$ ) ~~and~~ moderately affected by SWC (CV  $\sim 85\%$ ), Ts (%), and weakly by  
 605 RH (CV  $\sim 40\%$ ). Repeating the models applied by Grünzweig et al. (2009), the potential climatic factors that best predicted daily Rs shifted from  
 606 SWC and PAR in the dry season to Ts and PAR in the wet season (Table S2SI-2). These equations explained 43% and 70% of the variation in Rs  
 607 in the dry and wet seasons, respectively (Table S2SI-2). A reasonable forecast of the temporal variations in Rs ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) at half-hour values ( $R^2$   
 608  $= 0.60$ ,  $p < 0.0001$ ) ~~werewas~~ obtained based on SWC<sub>0-10</sub> and Ts values across the entire seasonal cycle, based on:

$$Rs = 0.05126 * \exp(0.04274 * Ts + 28.51 * SWC - 74.44 * SWC^2) \quad (13)$$

610  
 611 At the ecosystem scale, Re was characterized by high fluxes in the wet season and peak values of  $\sim 2.4 \mu\text{mol m}^{-2} \text{s}^{-1}$  in February to April (Fig. 2;  
 612 Table S4SI-1). Refluxes rapidly decreased after ~~rainy~~ the cessation of rain and reached the lowest values in the fall (~~September~~ September  
 613 to October), with mean dry period values of  $0.5 \pm 0.1 \mu\text{mol m}^{-2} \text{s}^{-1}$  (Fig. 2, Table S4SI-1). GPP had a mean value of  $-1.8 \pm 0.4 \mu\text{mol m}^{-2} \text{s}^{-1}$ , and daily  
 614 NEE had a mean value of  $-0.5 \pm 0.3 \mu\text{mol m}^{-2} \text{s}^{-1}$  (Table S4SI-1 and Fig. S5SI-6), with the same seasonality (Fig. 2).

615 **Table 2**  $\delta^{13}\text{C}$  and  $\Delta^{14}\text{C}$  signature of soil respiration (Rs) and its partitioning to autotrophic (Rsa), heterotrophic (Rh), and ~~the~~ abiotic (Ri), together with the relative  
 616 contribution of each to the soil and ecosystem respiration for Yatir forest during eight campaigns of measurements from January to September 2016 (numbers in  
 617 parenthesis indicate  $\pm \text{se}$ ) ~~in comparison to results obtained previously in the same forest (2001–2006 mean values)~~. The monthly contribution of Rsa, Rh, and Ri  
 618 to Rs or Re ~~are~~ is presented in Fig. 3a and b, respectively.

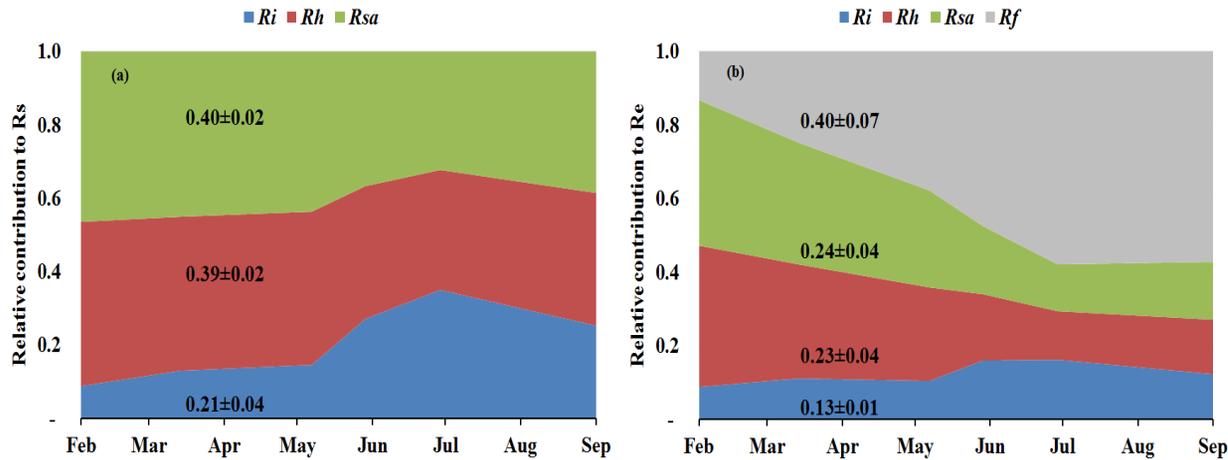
Signature	Rsa	Rh	Ri	Rs
	[‰]			
$\delta^{13}\text{C}$	-23.7 (0.5) <sup>1</sup>	-24.3 (0.0) <sup>1</sup>	-6.5 (0.0) <sup>1</sup>	-20.8 ( $\pm 0.6$ ) <sup>1</sup>
$\Delta^{14}\text{C}$	30 <sup>3</sup>	50 <sup>3</sup>	-900 <sup>2</sup>	-134 (34) <sup>4</sup>
<b>Relative contribution to Rs (2015–2016)</b>	<b>0.40 (0.02)</b>	<b>0.39 (0.02)</b>	<b>0.21 (0.04)</b>	
<b>Relative contribution to Re (2015–2016)</b>	<b>0.24 (0.04)</b>	<b>0.23 (0.04)</b>	<b>0.13 (0.01)</b>	<b>0.60 (0.06)</b>

620 <sup>1</sup> Measured ~~at~~ in the present study.

621 ~~);<sup>2</sup> Measured~~ measured by Carmi et al., (2013);  
 622 ~~);<sup>3</sup> Calculated~~ calculated based on the measured atmospheric value by Carmi et al., (2013);  
 623 ~~);<sup>4</sup> Calculated~~ calculated based on the best fit ~~regreicio~~ regression equation in ~~Figure S2~~ Fig. SI-2.

624  
 625 Figure 3 (see also Table 2) summarizes the seasonal variations in Rs and Re partitioning. The monthly Rsa and Rh were not significantly different  
 626 but were significantly different from Ri ( $p < 0.05$ ). The Rsa/Rs ratios ranged from 0.32 to 0.46, ~~with~~ the largest contribution occurring in early spring  
 627 from ~~February to February~~ February to April. The Rh/Rs fraction ranged between 0.33 and 0.45, being highest during the wet season. The Ri/Rs ~~– the~~ fraction  
 628 of ~~total respiration from~~ inorganic sources ~~from the total soil respiration~~ – ranged from 0.09 to 0.35, ~~with~~ the largest contribution being in the driest  
 629 period. The mean relative ~~contribution~~ contributions of these components to Rs over the sampling campaigns are presented in Figure 3a, but, on  
 630 average, soil biotic fluxes were higher than abiotic fluxes by a factor of ~4. Repartitioning showed an average increase in Rf/Re from 25-% in the  
 631 wet season to 54-% in the dry season and a decline in Rs/Re from 75-% to 46-% on average in the wet and the dry seasons, respectively, which  
 632 reflected a seasonal change of Rf in the wet season to peak values in the dry season (Fig. 3b). Both the highest and lowest Rs fractions (~0.74 and  
 633 nearly 0.34) along the seasonal cycle were associated with low total Re fluxes, that is, in the fall before the Rf peak in the spring and in the summer,  
 634 when physiological controls limited water loss.

635



636 **Figure 3+** a) Linear mixing models  $\delta^{13}\text{C}$  and  $\Delta^{14}\text{C}$  of soil respiration (Rs) isotope signatures (from soil  $\text{CO}_2$  profile method at 0, 30, 60, 90, and 120 cm soil depth)  
 637 were used to determine the seasonal variations in the relative contribution of soil autotrophic (Rsa), heterotrophic (Rh), and abiotic (Ri) components to Rs, and b)  
 638 seasonal variations in the relative contribution of soil autotrophic (Rsa), heterotrophic (Rh), abiotic (Ri), and foliage and stem respiration (Rf is obtained from the  
 639  $\text{Re}-\text{Rs}$ ) components to ecosystem respiration (Re) during Eight campaigns (Jan–Sep) in 2016. These results confirmed earlier estimates of Grünzweig et al.  
 640 (2009) and Maseyk et al. (2008a).

### 641 3.43. Annual scale

642 **Table 3+** Mean annual values of ecosystem respiration (Re), its components and associated ratios, net ecosystem exchange (NEE; from eddy covariance), net  
 643 primary productivity (NPP), gross primary productivity (GPP), carbon-use efficiency (CUE), leaf area index (LAI), and ratio of total belowground  
 644 Carbon allocation (TBCA) to GPP (TBCA/GPP) in the present study (mean of Nov–2015 to Oct–2016) and in comparison to results obtained previously  
 645 at the same site (2001–2006 mean values). Ri, Rh, Rsa, Rs, Rl and Rw denote abiotic, heterotrophic, soil autotrophic, soil, foliage, and wood  $\text{CO}_2$  flux, A  
 646 indicates the difference between the mean values for the two studies; using mean values for the two study periods respectively.  $Q_{10}$  asis derived during the two  
 647 studies for the wet and dry season.

Study	Rs	Rh	Rsa	Rl	Rw	Ri	Re	NEE	NPP	GPP
	[g m <sup>-2</sup> y <sup>-1</sup> ]									
Mean (2001–2006)	406	147	203	260	70	56	735	-211	-358	-880
<u>x/Rs</u>	<u>0.08</u>	<u>0.1936</u>	<u>0.2950</u>	<u>0.55</u>	<u>0.35</u>	<u>0.1014</u>				
<u>x/Re</u>	0.55	0.20	0.28	0.35	0.10	0.07				
Mean (2015–2016)	295	115	119	155	39	61	488	-167	-282	-655
<u>x/Rs</u>		<u>0.39</u>	0.40			<u>0.21</u>				
<u>x/Re</u>	0.60	0.23	0.24	0.32	0.08	0.13				
<u>Ratio of (x/Rs)<sub>2016</sub>/(x/Rs)<sub>2003</sub></u>		<u>1.08</u>	<u>0.81</u>			<u>1.50</u>				
<u>x/GPP</u> <u>Ratio of</u>	<u>0.09</u>	<u>0.18</u>	<u>0.1888</u>	<u>0.4590</u>	<u>0.2484</u>	<u>0.0616</u>	<u>0.75</u>	<u>0.25</u>	<u>0.42</u>	
Study	$Q_{10}$		CUE	TBCA/GPP <sup>3</sup>	LAI					
	SWC <sup>1</sup>	SWC <sup>2</sup>			[m <sup>2</sup> m <sup>-2</sup> ]					
Mean (2001–2006)	2.5	1.2	0.40	0.41	1.3					
Mean (2015–2016)	1.6	1.1	0.43	0.38	2.1					
<u>Ratio of x<sub>2016</sub>/x<sub>2003</sub></u>	<u>0.64</u>	<u>0.92</u>	<u>1.06</u>	<u>0.93</u>	<u>1.62</u>					

648  
 649 <sup>1</sup> SWC<sub>≥0.2</sub> [m<sup>3</sup> m<sup>-3</sup>]; <sup>2</sup> SWC<sub><0.2</sub> [m<sup>3</sup> m<sup>-3</sup>]; <sup>3</sup> and the mean of GPP used by Grünzweig et al., 2009 to estimate the TBCA/GPP was 834 g m<sup>-2</sup> y<sup>-1</sup>.

650 On an annual time-scale, estimates of  $\text{CO}_2$  flux components based on EC measurements resulted in annual values of GPP, NPP, Re, and  
 651 NEP of 655, 282, 488, and 167 g C m<sup>-2</sup> y<sup>-1</sup>, respectively (Tables 3 and S4SI-1). On average across the measurement period, Rs was the main  $\text{CO}_2$   
 652 flux into atmosphere, making up  $60 \pm 6\%$  of Re ( $295 \pm 4$  g C m<sup>-2</sup> y<sup>-1</sup>; Tables 3 and S4SI-1), and Rf was another significant component accounting

653 for  $40 \pm 6\%$  of  $R_e$  (Fig. 3b), which reflected the low density ( $300 \text{ trees ha}^{-1}$ ) nature of the semi-arid forest. As indicated above,  $R_e$  partitioning  
 654 showed a decrease in  $R_s/R_e$  and an increase in  $R_f/R_e$  from winter to summer, which is clearly apparent in Fig. 3b. On an annual scale, during the  
 655 study period, estimates of  $R_f$ ,  $R_{sa}$ ,  $R_h$ , and  $R_i$  values were  $194 \pm 36$ ,  $119 \pm 21$ ,  $115 \pm 20$ , and  $61 \pm 6 \text{ g C m}^{-2} \text{ y}^{-1}$ , respectively. Despite relatively high  
 656 rates of respiration fluxes, the CUE of the ecosystem remained high at 0.43.

657 **Table 4** | Linear regression over time of ecosystem respiration ( $R_e$ ), its components and associated ratios, net ecosystem exchange (NEE; from eddy covariance),  
 658 net primary productivity (NPP), gross primary productivity (GPP), total belowground Carbon allocation (TBCA), and ratio of TBCA/GPP (2001–2016) in the semi-  
 659 arid pine forest site.  $R_h$ ,  $R_s$ , and  $R_f$  denote heterotrophic, soil, and foliage and wood  $\text{CO}_2$  flux. The model parameters (slope and intercept) reported for each variable  
 660 together with the squared coefficient of regression ( $R^2$ ) and the  $P$ -value. The data for the regression analysis includes 15 years (2001–2016) of the site’s flux records  
 661 of  $R_e$ , NEE, GPP, NPP; and from comparing the data from the earlier 2001–2006 to the present stud (Nov 2015–Oct 2016) for 7 years of  $R_s$ ,  $R_h$ ,  $R_f$ , and TBCA  
 662 and TBCA/GPP.

Variables	Linear regression			
	Slope	Interecept	$R^2$	$P$ -value
<b>Re</b>	1.0	386	0.0	0.819
<b>Rs</b>	-11.0	436	0.6	0.036
<b>Rh</b>	-3.9	159	0.1	0.404
<b>Rf</b>	-7.1	341	0.3	0.180
<b>NEE</b>	9.0	-231	0.2	0.065
<b>GPP</b>	8.0	-617	0.1	0.254
<b>NPP</b>	-8.8	304	0.2	0.083
<b>TBCA</b>	-9.4	367	0.5	0.114
<b>TBCA/GPP</b>	-0.006	0.43	0.2	0.416

663

664 Using the site records of nearly 20 years, long-term trends in GPP, NPP,  $R_e$ , and NEP were obtained. Comparison of Soil respiration and its  
 665 partitioning could not be similarly monitored continuously, but combining the present results with the 2001–2006 values obtained by Grünzweig et  
 666 al. (2009) and Maseyk et al. (2008a) provided a basis for estimating the temporal long-term trends in soil respiration. Notably, no clear or significant  
 667 trend over time was observed in any of the canopy-scale fluxes (Table 4). However, the soil respiration rates,  $R_s$ , decreased significantly by  $11 \pm 4$

668  $\text{g C m}^{-2} \text{y}^{-1}$  ( $R^2=0.62$ ,  $p=0.036$ ; Table 4) from regression of the 2001–2006 value to the mean value in the present study (Nov 2015–Oct 2016).  
669 ~~Because of strong influenced of variations in environmental conditions, primarily precipitation on interannual variations, continuously monitored~~  
670 ~~fluxes, but, because of relatively large interannual variations, associated mainly with those in precipitation (see Qubaja et al., in press), it is likely~~  
671 that the relative contributions of the different fluxes, expressed as ratios in Table 3, provide a relatively more robust perspective of the long-term  
672 temporal changes in the ecosystem functioning. ~~Based on long-term The results presented in Table 3,  $R_f/R_e$  ( $R_f$  ratio) decreased by 11 % while~~  
673  ~~$R_s/R_e$  ( $R_s$  ratio) increased by 9 % over reflect the long-term growth of the forest, with a relatively large increase in LAI, but the belowground~~  
674 ~~allocation remained around 40%. The ratio of the respiration components to total ecosystem respiration,  $R_e$ , or to GPP indicated little change in the~~  
675 ~~total soil respiration,  $R_s$ , component, but a general shift from the autotrophic components  $R_{sa}$ ,  $R_l$ , and  $R_w$  to the heterotrophic component,  $R_h$ ,~~  
676 ~~across the 13-year observation period noted above (essentially 2003 to 2016). Notably, LAI increased across the same observation period from 1.3~~  
677 ~~to 2.1 (+57 %; Qubaja et al., unpublished), indicating that the  $\Delta R_f$  ratio/ $\Delta$ LAI decreased ( $-0.05/0.75=-0.07$ ), and the  $\Delta R_s$  ratio/ $\Delta$ LAI increased~~  
678 ~~( $+0.05/0.75=+0.07$ ; Table 3). These results highlight the shift from  $R_f$  to  $R_s$  over the 13 years observation period. Total TBCA was  $247 \text{ g C m}^{-2} \text{y}^{-1}$~~   
679 ~~during the study period and relative below ground partitioning of carbon in the ecosystem (TBCA/GPP) averaged 38%, which was lower than with~~  
680 ~~the previous study by 7 % mean values for 2011–2005 assigned to 2003 and the same site (Grünzweig et al., 2009 new data to 2016).~~

#### 681 4. Discussion

682 Partitioning ecosystem carbon fluxes and long-term observational studies are key to understanding ecosystem carbon dynamics and their response  
683 to change. ~~This research hypothesized that soil  $\text{CO}_2$  efflux at the dry study site is a key factor underlying the observation of high NEP and high CUE~~  
684 ~~in this system. Overall, the results support our research hypothesis that the observed high CUE at our site is at least partly due to the characteristics~~  
685 ~~of the carbon flux partitioning that can be associated with the semi-arid conditions. Compared to other sites and climates (see comparative~~  
686 ~~compilation in Table SI-3), the results reflect several key points: 1) relatively high belowground allocation; 2) low soil respiration in general, and~~  
687 ~~low heterotrophic respiration in particular; 3) combining the results for 2016 and those of our earlier study offered a long-term perspective across~~  
688 ~~13 years, indicating that the low  $R_s$  in this ecosystem is robust and exhibits reduced sensitivity to temperature, and 4) there is a general long-term~~  
689 ~~shift from autotrophic to heterotrophic respiration.~~

690 Comparing CO<sub>2</sub> fluxes in this forest with fluxes in a range of European forests showed that mean NEP in the semi-arid forest (167 g C m<sup>-2</sup> y<sup>-1</sup>) ~~was~~  
691 similar to the mean NEP ~~across~~ other European forests (150 g C m<sup>-2</sup> y<sup>-1</sup>; FLUXNET).

692 Carbon partitioning belowground (TBCA/GPP) was relatively high (~38%), with little change across the long-term observation period. It is, however,  
693 within the range of mean value for forests in different biomes (Litton et al., 2007). High belowground allocation helps explain the high rate of SOC  
694 accumulation observed over the period since afforestation (Grünzweig et al., 2007; Qubaja et al., in press). Note that, irrespective of the soil carbon  
695 accumulation, the abiotic component to the CO<sub>2</sub> flux seems to be significant in dry environments (Table 3) and in particular in the dry seasons, when  
696 biological activities drastically decrease (Kowalski et al., 2008; Lopez-Ballesteros et al., 2017; Serrano-Ortiz et al., 2010; Martí-Roura et al., 2019).  
697 The results show that considering the abiotic effects on estimating soil respiration and, in turn, on estimating the carbon budget in dry calcareous  
698 soils can play an important part in estimating soil and ecosystem respiration fluxes (Angert et al., 2015; Roland et al., 2012).

699 ~~In contrast, The~~ soil CO<sub>2</sub> efflux in the semi-arid forest ~~was~~ (295 g C m<sup>-2</sup> y<sup>-1</sup>, ~~which~~) is at the low end of Rs values across the range ~~for other~~ climatic  
700 regions, from 50 to ~~27502.750~~ 275 g C m<sup>-2</sup> y<sup>-1</sup> (Adachi et al., 2017; ~~Bond Lamberty, 2018~~; Chen et al., 2014; Grünzweig et al., 2009; Hashimoto et al.,  
701 2015). This is clearly lower than the mean Rs value for global evergreen needle forests, which is estimated at 690 g C m<sup>-2</sup> y<sup>-1</sup> (Chen et al., 2014),  
702 and between estimates for desert scrub and Mediterranean woodland (224–713 g C m<sup>-2</sup> y<sup>-1</sup>; Raich and ~~Schlesinger, 1992~~). ~~The mean~~ Schlesinger,  
703 1992) or for Mediterranean forests (561–1,015 g C m<sup>-2</sup> y<sup>-1</sup>; Casals et al., 2011; Luysaert et al., 2007; Matteucci et al., 2015; Misson et al., 2010;  
704 Rey et al., 2002; Rodeghiero and Cescatti, 2005). The mean instantaneous rate of Rs, 0.8 μmol m<sup>-2</sup> s<sup>-1</sup>, is also in the range reported for unmanaged  
705 forest and grassland in the dry Mediterranean region (0.5 and 2.1 μmol m<sup>-2</sup> s<sup>-1</sup>; Correia et al., ~~2012~~). ~~High productivity associated with low Rs~~  
706 ~~supports the high CUE estimate and the carbon sequestration potential of the semi-arid Aleppo pin plantation (Rotenberg and Yakir, 2010).2012).~~

707 ~~The spatial variations in Rs among the microsites (Table 1) can be approximated to estimate the possible impact on Rs caused by changes in forest~~  
708 ~~density associated with a drying climate (e.g., tree thinning and mortality). For example, decreasing from the present optimal stand density (Raz-~~  
709 ~~Yaseef et al., 2010) of 300 trees ha<sup>-1</sup> to 100 trees ha<sup>-1</sup> would result, based on present results, in decreasing ecosystem Rs and increasing soil~~  
710 ~~evaporation (Es) by 11 % and 38 %, respectively. This is consistent with the trend for increasing stand density (Litton et al., 2004) and the effects~~

711 of stand density on Rs through effected litterfall, TBCA, and total soil N (Noh et al., 2010). More work is needed to determine the net effects of such  
712 changes (see Maseyk et al., 2011; Villegas et al., 2015).

713 ~~Low~~observed low Rs values were associated with a relatively high ~~rates~~fraction of autotrophic ~~respiration, with and~~ a lower fraction of heterotrophic  
714 ~~respiration. The~~ mean annual-scale Rsa/Rs ratio of 0.40, ~~which is similar to~~ was at the ~~estimated high end of the~~ global ~~mean value within the~~ range  
715 of 0.09 to 0.49 (Chen et al., 2014; Hashimoto et al., 2015). ~~Heterotrophic~~In contrast, heterotrophic respiration ~~was of the same magnitude (showed~~  
716 ~~an~~ annual-scale Rh/Rs ratio: ~~of~~  $0.39 \pm 0.02$  (Table 2 and Fig. 3), which ~~reflected an increasing trend of +14 % from mean 2001-2006 values~~  
717 ~~(Grünzweig et al., 2009; Maseyk et al., 2008a) to the mean values in the present study. This ratio is lower than the estimated global mean Rh/Rs~~  
718 ~~value of 0.56 (Hashimoto et al., 2015)), but comparable to~~within the ~~long term trend~~range of ~~+17 %~~Mediterranean region forest, which varies  
719 between ~~1990 and 2014 (Bond-Lamberty et al., 2018). The seasonal dynamics in Rs partitioning (Fig. 3) might reflect an increasing balance between~~  
720 ~~Rsa and Rh compared to Rsa dominance in the dry season, which was present in the earlier study (Grünzweig et al., 2009; Maseyk et al., 2008a; see~~  
721 ~~also Carbone et al., 2008, Tang et al., 2005).~~

722 ~~Carbon partitioning below ground (TBCA/GPP) was relatively high at 0.38, despite a ~7 % decrease in values compared to those reported by~~  
723 ~~Grünzweig et al. (2009) but was similar to the mean value for forests in various biomes (Litton~~29 to 0.77 (Casals et al., 2011; Luysaert et al., 2007).  
724 ~~This explains; Matteucci et al., 2015; Misson et al., 2010; Rey et al., 2002; Rodeghiero and Cescatti, 2005). the high rate of SOC accumulation~~  
725 ~~observed over the period since afforestation (Grünzweig et al., 2007; Qubaja et al., unpublished). The ratio of Rs/GPP did not change over the~~  
726 ~~observation period (0.46 vs. 0.45 for 2001-2006 vs. 2015-2016 mean values) but shifted to a larger contribution of Rh (Table 3).~~

727 The relatively low annual scale of the heterotrophic respiration to Rs ~~was~~is consistent with the dry ~~surface~~soil ~~layer~~over much of the year in this  
728 forest (~~Figures~~Figs 2 and S5SI-6) and the observed low decomposability of plant detritus and high mean SOC accumulation rate (Grünzweig et al.,  
729 2007). The ~~small increase in Rh proportional contribution to Rs may reflect the general climatic trends in the region of increasing temperature, with~~  
730 ~~no significant change in precipitation (Bond-Lamberty et al., 2018).~~2007).

731 The long-term perspective from the 13-year observation period indicates emerging trends that can be a basis for assessing the effects of forest age  
732 and the marked increase in LAI (Table 3) and changes in environmental conditions (generally warming and drying; see, e.g., Lelieveld et al., 2012).  
733 As noted above, comparing the non-continuous data from the present (2016) and earlier (2001–2006) studies is sensitive to the large interannual  
734 variations in the ecosystem activities and fluxes (Qubaja et al., in press), and we therefore focused on the more robust changes in the ratio of the  
735 respiration components to the overall fluxes (Re) (Table 3). This shows a shifting trend from the autotrophic components to the heterotrophic, with  
736 little change in the contribution of Rs to the overall efflux. The ratios of Rsa, Rl, and Rw to Re tended to decrease by about 13%, while that of Rh  
737 increased by about 18%; similar trends were seen in soil respiration, with Rsa/Rs decreasing by -19% and Rh/Rs increasing by +8% (Table 3). The  
738 relatively low Rs under conditions of high temperature in the semi-arid ecosystem implies reduced ~~to~~ sensitivity of respiration to temperature. This  
739 is partly imposed by low SWC conditions during extended parts of the year (Grünzweig et al., 2009; cf. Rey et al., 2002; Xu and Qi, 2001).  
740 Accordingly, Rs ~~varied with~~ showed greater sensitivity to Ts ~~only under relatively in the~~ wet ~~conditions~~ period, but during the 8–9 months of the year  
741 when SWC was below a ~~threshold value of~~  $\sim 0.2 \text{ m}^3 \text{ m}^{-3}$ , Rs varied predominantly with water availability. The ~~R<sub>s</sub> vs. T<sub>s</sub> relationship used to estimate~~  
742 apparent long-term perspective reported in Table 3 indicates a further decrease in temperature sensitivity, with mean  $Q_{10}$  values ~~indicated a decrease~~  
743 in the dry season decreasing from  $Q_{10} = 1.6$  in the wet season to  $Q_{10} = 1.1$  in the dry season. This represents a similar trend in  $Q_{10}$  compared to the  
744 results of Grünzweig et al. (2009; Table 3). The These estimated  $Q_{10}$  values are generally consistent with published values ~~that range from 1.4 to~~  
745 2.0 ~~among for~~ different ecosystems (1.4 to 2.0; Hashimoto et al., 2015; Zhou et al., 2009) and with low values under low SWC (Reichstein et al.,  
746 2003; Tang et al., 2005). ~~The~~ This is also consistent with soil warming experiments by 0.76°C in Mediterranean ecosystems, which decreased the Rs  
747 by 16%, and  $Q_{10}$  by 14% (Wang et al., 2014). Note also that the low temperature sensitivity in the dry season ~~must~~ is likely to be related to reduced  
748 microbial activity, but may also involve ~~down regulation~~ downregulation of ~~the~~ plant activity (Maseyk et al., 2008a) and drought-induced dormancy  
749 of shallow roots (Schiller, 2000). ~~Little is known about the differences in  $Q_{10}$  of soil Rh and Rsa respirations (Yu et al., 2017), which could respond~~  
750 differently to different environmental variables (Matteucci et al., 2015) and make ~~distinct contributions to soil carbon sequestration (Kuzyakov,~~  
751 2006). Previous studies have shown that Rh and Rsa exhibit different temperature sensitivities (Rey et al., 2002), but the underlying causes of the  
752 temporal changes observed in the  $Q_{10}$  values at the study sites in this study remain uncertain Finally, we also note that the greater importance of  
753 moisture availability in influencing respiration is clearly apparent from the observed relationships of Rs and Rh to mean annual precipitation (MAP)  
754 in European evergreen needle forests (Fig. SI-8; see also Grünzweig et al., 2007), which are not observed with respect to mean annual temperature.

755 *Data availability*

756 The data used in this study are archived and available from the corresponding author upon request ([dan.yakir@weizmann.ac.il](mailto:dan.yakir@weizmann.ac.il)).

757 *Author contributions*

758 RQ and DY designed the study; RQ, FT, ER and DY performed the experiments. RQ and DY analyzed the data. DY and RQ wrote the paper, with  
759 discussions and contributions to interpretations of the results from all co-authors.

760 *Competing interests*

761 The authors declare that they have no conflict of interest.

762 **5. Acknowledgements**

763 This long-term study was funded by the Forestry Department of Keren-Kayemeth-LeIsrael (KKL) and the German Research Foundation (DFG) as  
764 part of the project “Climate feedback and benefits of semi-arid forests” (Cliff) and by the Israel Ministry of Science and the Ministry of National  
765 Education, Higher Education, and Research (MENESR) of France (IMOS-French Program: 3-6735). The authors thank Efrat Schwartz for assistance  
766 with lab work. The long-term operation of the Yatir Forest Research Field Site is supported by the Cathy Wills and Robert Lewis Program in  
767 Environmental Science. We thank the entire Yatir team for technical support and the local KKL personnel for their cooperation.

768 **6. References**

- 769 Adachi, M., Ito, A., Yonemura, S., & Takeuchi, W. (2017). Estimation of global soil respiration by accounting for land-use changes derived from remote sensing  
770 data. *Journal of Environmental Management*, 200, 97-104.
- 771 ~~Agam, N., & Berliner, P. R. (2004). Diurnal water content changes in the bare soil of a coastal desert. *Journal of Hydrometeorology*, 5(5), 922-933.~~  
772 ~~doi:10.1175/1525-7541(2004)005<0922:dweeit>2.0.co;2~~
- 773 ~~Andersen, C. P., Nikolov, I., Nikolova, P., Matyssek, R., & Haberle, K. H. (2005). Estimating "autotrophic" belowground respiration in spruce and beech forests:~~

- 774 ~~decreases following girdling. *European Journal of Forest Research*, 124(3), 155-163.~~
- 775 Angert, A., Yakir, D., Rodeghiero, M., Preisler, Y., Davidson, E. A., & Weiner, T. (2015). Using O-2 to study the relationships between soil CO2 efflux and soil
- 776 respiration. *Biogeosciences*, 12(7), 2089-2099.
- 777 Aubinet, M., Grelle, A., Ibrom, A., Rannik, U., Moncrieff, J., Foken, T., et al. (2000). Estimates of the annual net carbon and water exchange of forests: The
- 778 EUROFLUX methodology. *Advances in Ecological Research*, Vol 30, 30, 113-175.
- 779 ~~Aubrey, D. P., & Teskey, R. O. (2009). Root derived CO2 efflux via xylem stream rivals soil CO2 efflux. *New Phytologist*, 184(1), 35-40.~~
- 780 Bahn, M., Janssens, I. A., Reichstein, M., Smith, P., & Trumbore, S. E. (2010). Soil respiration across scales: towards an integration of patterns and processes.
- 781 *New Phytologist*, 186(2), 292-296.
- 782 ~~Ballantyne, A. P., Andres, R., Houghton, R., Stocker, B. D., Wanninkhof, R., Anderegg, W., et al. (2015). Audit of the global carbon budget: estimate errors and~~
- 783 ~~their impact on uptake uncertainty. *Biogeosciences*, 12(8), 2565-2584.~~
- 784 Balogh, J., Pinter, K., Foti, S., Cserhalmi, D., Papp, M., & Nagy, Z. (2011). Dependence of soil respiration on soil moisture, clay content, soil organic matter, and
- 785 CO2 uptake in dry grasslands. *Soil Biology & Biochemistry*, 43(5), 1006-1013.
- 786 ~~Benavente, J., Vadillo, I., Carrasco, F., Soler, A., Linan, C., & Moral, F. (2010). Air Carbon Dioxide Contents in the Vadose Zone of a Mediterranean Karst.~~
- 787 ~~*Vadose Zone Journal*, 9(1), 126-136.~~
- 788 Binkley, D., Stape, J. L., Takahashi, E. N., & Ryan, M. G. (2006). Tree-girdling to separate root and heterotrophic respiration in two Eucalyptus stands in Brazil.
- 789 *Oecologia*, 148(3), 447-454.
- 790 ~~Bloemen, J., Agneessens, L., Van Meulebroek, L., Aubrey, D. P., McGuire, M. A., Teskey, R. O., et al. (2014). Stem girdling affects the quantity of CO2 transported~~
- 791 ~~in xylem as well as CO2 efflux from soil. *New Phytologist*, 201(3), 897-907.~~
- 792 Bonan, G. B. (2008). *Ecological climatology : concepts and applications* (2nd ed.. ed.). Cambridge: Cambridge : Cambridge University Press.
- 793 ~~Bond-Lamberty, B. (2018). *New Techniques and Data for Understanding the Global Soil Respiration Flux. *Earths Future*, 6(9), 1176-1180.*~~
- 794 ~~Bond-Lamberty, B., & Thomson, A. (2010). Temperature-associated increases in the global soil respiration record. *Nature*, 464(7288), 579-U132.~~
- 795 ~~Bond-Lamberty, B., Bailey, V. L., Chen, M., Gough, C. M., & Vargas, R. (2018). Globally rising soil heterotrophic respiration over recent decades. *Nature*,~~
- 796 ~~560(7716), 80+.~~
- 797 Buchmann, N. (2000). Biotic and abiotic factors controlling soil respiration rates in *Picea abies* stands. *Soil Biology & Biochemistry*, 32(11-12), 1625-1635.
- 798 ~~Cable, J. M., Ogle, K., Lucas, R. W., Huxman, T. E., Loik, M. E., Smith, S. D., et al. (2011). The temperature responses of soil respiration in deserts: a seven desert~~
- 799 ~~synthesis. *Biogeochemistry*, 103(1-3), 71-90.~~
- 800 Carbone, M. S., Winston, G. C., & Trumbore, S. E. (2008). Soil respiration in perennial grass and shrub ecosystems: Linking environmental controls with plant
- 801 and microbial sources on seasonal and diel timescales. *Journal of Geophysical Research-Biogeosciences*, 113(G2).
- 802 Carmi, I., Yakir, D., Yechieli, Y., Kronfeld, J., & Stiller, M. (2013). VARIATIONS IN SOIL CO2 CONCENTRATIONS AND ISOTOPIC VALUES IN A SEMI-
- 803 ARID REGION DUE TO BIOTIC AND ABIOTIC PROCESSES IN THE UNSATURATED ZONE. *Radiocarbon*, 55(2-3), 932-942.
- 804 Carvalhais, N., Forkel, M., Khomik, M., Bellarby, J., Jung, M., Migliavacca, M., et al. (2014). Global covariation of carbon turnover times with climate in terrestrial
- 805 ecosystems. *Nature*, 514(7521), 213-+.
- 806 ~~Casals, P., Lopez-Sangil, L., Carrara, A., Gimeno, C., & Nogues, S. (2011). Chapin, F. S., III, Woodwell, G. M., Randerson, J. T., Rastetter, E. B., Lovett, G. M.,~~
- 807 ~~Baldocchi, D. Autotrophic and heterotrophic contributions to short-term soil CO2 efflux following simulated summer precipitation pulses in a Mediterranean~~
- 808 ~~dehesa. *Global Biogeochemical Cycles*, 25. doi:10.1029/2010gb003973~~
- 809 ~~D., et al. (2006). Reconciling carbon cycle concepts, terminology, and methods. *Ecosystems*, 9(7), 1041-1050.~~
- 810 Chen, D., Zhang, Y., Lin, Y., Zhu, W., & Fu, S. (2010). Changes in belowground carbon in *Acacia crassicarpa* and *Eucalyptus urophylla* plantations after tree
- 811 girdling. *Plant and Soil*, 326(1-2), 123-135.

812 Chen, S. T., Zou, J. W., Hu, Z. H., Chen, H. S., & Lu, Y. Y. (2014). Global annual soil respiration in relation to climate, soil properties and vegetation characteristics:  
813 Summary of available data. *Agricultural and Forest Meteorology*, 198, 335-346.

814 Conant, R. T., Klopatek, J. M., Malin, R. C., & Klopatek, C. C. (1998). Carbon pools and fluxes along an environmental gradient in northern Arizona.  
815 *Biogeochemistry*, 43(1), 43-61.

816 Correia, A. C., Minunno, F., Caldeira, M. C., Banza, J., Mateus, J., Carneiro, M., . . . Pereira, J. S. (2012). Soil water availability strongly modulates soil CO2  
817 efflux in different Mediterranean ecosystems: Model calibration using the Bayesian approach. *Agriculture Ecosystems & Environment*, 161, 88-100.  
818 doi:10.1016/j.agee.2012.07.025

819 ~~Cuezva, S., Fernandez-Cortes, A., Benavente, D., Serrano-Ortiz, R., Kowalski, A. S., & Sanchez-Moral, S. (2011). Short-term CO2(g) exchange between a shallow  
820 karstic cavity and the external atmosphere during summer: Role of the surface soil layer. *Atmospheric Environment*, 45(7), 1418-1427.~~

821 Davidson, E. A., & Janssens, I. A. (2006). Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature*, 440(7081), 165-173.

822 ~~Davidson, E. A., Belk, E., & Boone, R. D. (1998). Soil water content and temperature as independent or confounded factors controlling soil respiration in a  
823 temperate mixed hardwood forest. *Global Change Biology*, 4(2), 217-227.~~

824 DeLucia, E. H., Drake, J. E., Thomas, R. B., & Gonzalez-Meler, M. (2007). Forest carbon use efficiency: is respiration a constant fraction of gross primary  
825 production? *Global Change Biology*, 13(6), 1157-1167.

826 Deng, Q., Hui, D., Zhang, D., Zhou, G., Liu, J., Liu, S., et al. (2012). Effects of Precipitation Increase on Soil Respiration: A Three-Year Field Experiment in  
827 Subtropical Forests in China. *Plos One*, 7(7).

828 ~~Etzold, S., Ruehr, N. K., Zweifel, R., Dobbertin, M., Zingg, A., Pluess, P., et al. (2011). The Carbon Balance of Two Contrasting Mountain Forest Ecosystems in  
829 Switzerland: Similar Annual Trends, but Seasonal Differences. *Ecosystems*, 14(8), 1289-1309.~~

830 ~~Etzold, S., Zweifel, R., Ruehr, N. K., Dirks, I., Navon, Y., Kanas, D., Dumbur, Eugster, W., & Buchmann, N. (2013). Long-term stem CO2 concentration  
831 measurements in Norway spruce in relation to biotic and abiotic factors. *New Phytologist*, 197(4), 1173-1184. doi:10.1111/nph.12115~~

832 ~~R., & Grunzweig, J. M. (2010). Atmospheric water vapor as driver of litter decomposition in Mediterranean shrubland and grassland during rainless seasons.  
833 *Global Change Biology*, 16(10), 2799-2812. doi:10.1111/j.1365-2486.2010.02172.x~~

834 ~~Eshel, G., Fine, P., & Singer, M. J. (2007). Total soil carbon and water quality: An implication for carbon sequestration. *Soil Science Society of America Journal*,  
835 71(2), 397-405. doi:10.2136/sssaj2006.0061~~

836 Falge, E., Baldocchi, D., Tenhunen, J., Aubinet, M., Bakwin, P., Berbigier, P., et al. (2002). Seasonality of ecosystem respiration and gross primary production as  
837 derived from FLUXNET measurements. *Agricultural and Forest Meteorology*, 113(1-4), 53-74.

838 ~~Flechar, C. R., Ibrm, A., Skiba, U. M., de Vries, W., van Oijen, M., Cameron, D. R., et al. (2019). Carbon / nitrogen interactions in European forests and semi-  
839 natural vegetation. Part I: Fluxes and budgets of carbon, nitrogen and greenhouse gases from ecosystem monitoring and modelling, *Biogeosciences Discuss.*,  
840 <https://doi.org/10.5194/bg-2019-333>, in review, 2019.~~

841 ~~Flechar, C. R., van Oijen, M., Cameron, D. R., de Vries, W., Ibrm, A., Buchmann, N., Dise, N. B., et al. (2019). Carbon / nitrogen interactions in European  
842 forests and semi-natural vegetation. Part II: Untangling climatic, edaphic, management and nitrogen deposition effects on carbon sequestration potentials,  
843 *Biogeosciences Discuss.*, <https://doi.org/10.5194/bg-2019-335>, in review, 2019.~~

844 Frank, A. B., Liebig, M. A., & Hanson, J. D. (2002). Soil carbon dioxide fluxes in northern semiarid grasslands. *Soil Biology & Biochemistry*, 34(9), 1235-1241.

845 Frey, B., Hagedorn, F., & Giudici, F. (2006). Effect of girdling on soil respiration and root composition in a sweet chestnut forest. *Forest Ecology and Management*,  
846 225(1-3), 271-277.

847 ~~Gelfand, I., Grünzweig, J. M., & Yakir, D. (2012). Slowing of nitrogen cycling and increasing nitrogen use efficiency following afforestation of semi-arid  
848 shrubland. *Oecologia*, 168(2), 563-575. doi:10.1007/s00442-011-2111-0~~

849 Giardina, C. P., & Ryan, M. G. (2002). Total belowground carbon allocation in a fast-growing Eucalyptus plantation estimated using a carbon balance approach.  
850 *Ecosystems*, 5(5), 487-499.

851 ~~Gliksman, D., Rey, A., Seligmann, R., Dumbur, R., Sperling, O., Navon, Y., . . . Grunzweig, J. M. (2017). Biotic degradation at night, abiotic degradation at day:~~  
852 ~~positive feedbacks on litter decomposition in drylands. *Global Change Biology*, 23(4), 1564-1574. doi:10.1111/geb.13465~~

853 Graven, H. D., Guilderson, T. P., & Keeling, R. F. (2012). Observations of radiocarbon in CO<sub>2</sub> at La Jolla, California, USA 1992-2007: Analysis of the long-term  
854 trend. *Journal of Geophysical Research-Atmospheres*, 117.

855 Grünzweig, J. M., Gelfand, I., Fried, Y., & Yakir, D. (2007). Biogeochemical factors contributing to enhanced carbon storage following afforestation of a semi-  
856 arid shrubland. *Biogeosciences*, 4(5), 891-904.

857 Grünzweig, J. M., Hemming, D., Maseyk, K., Lin, T., Rotenberg, E., Raz-Yaseef, N., et al. (2009). Water limitation to soil CO<sub>2</sub> efflux in a pine forest at the  
858 semiarid "timberline". *Journal of Geophysical Research-Biogeosciences*, 114.

859 Grünzweig, J. M., Lin, T., Rotenberg, E., Schwartz, A., & Yakir, D. (2003). Carbon sequestration in arid-land forest. *Global Change Biology*, 9(5), 791-799.

860 ~~Hagedorn, F., Joseph, J., Peter, M., Luster, J., Pritsch, K., Geppert, U., . . . Arend, M. (2016). Recovery of trees from drought depends on belowground sink control.~~  
861 ~~*Nature Plants*, 2(8). doi:10.1038/nplants.2016.111~~

862 Hashimoto, S., Carvalhais, N., Ito, A., Migliavacca, M., Nishina, K., & Reichstein, M. (2015). Global spatiotemporal distribution of soil respiration modeled using  
863 a global database. *Biogeosciences*, 12(13), 4121-4132.

864 ~~Heinemeyer, A., Hartley, I. P., Evans, S. P., De la Fuente, J. A. C., & Ineson, P. (2007). Forest soil CO<sub>2</sub> flux: uncovering the contribution and environmental~~  
865 ~~responses of ectomycorrhizas. *Global Change Biology*, 13(8), 1786-1797.~~

866 Hemming, D., Yakir, D., Ambus, P., Aurela, M., Besson, C., Black, K., . . . Vesala, T. (2005). Pan-European delta C-13 values of air and organic matter from  
867 forest ecosystems. *Global Change Biology*, 11(7), 1065-1093. doi:10.1111/j.1365-2486.2005.00971.x

868 Hogberg, P., Bhupinderpal, S., Lofvenius, M. O., & Nordgren, A. (2009). Partitioning of soil respiration into its autotrophic and heterotrophic components by  
869 means of tree-girdling in old boreal spruce forest. *Forest Ecology and Management*, 257(8), 1764-1767.

870 Hui, D. F., & Luo, Y. Q. (2004). Evaluation of soil CO<sub>2</sub> production and transport in Duke Forest using a process-based modeling approach. *Global Biogeochemical*  
871 *Cycles*, 18(4).

872 IPCC, (2014). *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental*  
873 *Panel on Climate Change* [Edenhofer, O., R. et al.]. Cambridge University Press, Cambridge and New York.

874 Jiang, H., Deng, Q., Zhou, G., Hui, D., Zhang, D., Liu, S., et al. (2013). Responses of soil respiration and its temperature/moisture sensitivity to precipitation in  
875 three subtropical forests in southern China. *Biogeosciences*, 10(6), 3963-3982.

876 ~~Joseph, J., Kulls, C., Arend, M., Schaub, M., Hagedorn, F., Gessler, A., & Weiler, M. (2019). Application of a laser-based spectrometer for continuous in situ~~  
877 ~~measurements of stable isotopes of soil CO<sub>2</sub> in calcareous and acidic soils. *Soil*, 5(1), 49-62. doi:10.5194/soil-5-49-2019~~

878 ~~Kool, D. M., Chung, H. G., Tate, K. R., Ross, D. J., Newton, P. C. D., & Six, J. (2007). Johnson, K., Maier, C., Sanchez, Hierarchical saturation of soil carbon~~  
879 ~~pools near a natural CO<sub>2</sub> spring. *Global Change Biology*, 13(6), 1282-1293. doi:10.1111/j.1365-2486.2007.01362.x~~

880 ~~Lelieveld, J., Hadjinicolaou, P., Kostopoulou, E., Chenoweth, J., El Maayar, M., Giannakopoulos, C., . . . Xoplaki, E. (2012). Climate change and impacts in the~~  
881 ~~Eastern Mediterranean and the Middle East. *Climatic Change*, 114(3-4), 667-687. doi:10.1007/s10584-012-0418-4~~

882 ~~F., Anderson, P., Butnor, J., Waring, R., et al. (2007). Physiological girdling of pine trees via phloem chilling: proof of concept. *Plant Cell and Environment*,~~  
883 ~~30(1), 128-134.~~

884 ~~Kappen, L., Lange, O. L., Schulze, E. D., Evenari, M., & Buschbom, U. (1979). ECOPHYSIOLOGICAL INVESTIGATIONS ON LICHENS OF THE NEGEV~~  
885 ~~DESERT .6. ANNUAL COURSE OF THE PHOTOSYNTHETIC PRODUCTION OF RAMALINA MACIFORMIS (DEL) BORY. *Flora*, 168(1-2), 85-108.~~

886 Köchy, M., Hiederer, R., & Freibauer, A. (2015). Global distribution of soil organic carbon—Part 1: Masses and frequency distributions of SOC stocks for the  
887 tropics, permafrost regions, wetlands, and the world. *Soil*, 1(1), 351-365.

888 Kosmas, C., Danalatos, N. G., Poesen, J., & van Wesemael, B. (1998). The effect of water vapour adsorption on soil moisture content under Mediterranean climatic  
889 conditions. *Agricultural Water Management*, 36(2), 157-168. doi:10.1016/s0378-3774(97)00050-4

890 Kowalski, A. S., Serrano-Ortiz, P., Janssens, I. A., Sanchez-Moral, S., Cuezva, S., Domingo, F., et al. (2008). Can flux tower research neglect geochemical CO<sub>2</sub>  
891 exchange? *Agricultural and Forest Meteorology*, 148(6-7), 1045-1054.

892 ~~Kuehn, K. A., Steiner, D., & Gessner, M. O. (2004). Diel mineralization patterns of standing dead plant litter: Implications for CO<sub>2</sub> flux from wetlands. *Ecology*,  
893 85(9), 2504-2518. doi:10.1890/03-4082~~

894 Kuzyakov, Y. (2006). Sources of CO<sub>2</sub> efflux from soil and review of partitioning methods. [Review]. *Soil Biology & Biochemistry*, 38(3), 425-448.

895 ~~Lange, O. L., Green, T. G. A., Melzer, B., Meyer, A., & Zellner, H. (2006). Water relations and CO<sub>2</sub> exchange of the terrestrial lichen *Teloschistes capensis* in the  
896 Namib fog desert: Measurements during two seasons in the field and under controlled conditions. *Flora*, 201(4), 268-280. doi:10.1016/j.flora.2005.08.003~~

897 ~~Le Quéré, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Pongratz, J., Manning, A. C., et al. (2018). Global Carbon Budget 2017. *Earth System Science Data*,  
898 10(1), 405-448.~~

899 Lellei-Kovacs, E., Kovacs-Lang, E., Botta-Dukat, Z., Kalapos, T., Emmett, B., & Beier, C. (2011). Thresholds and interactive effects of soil moisture on the  
900 temperature response of soil respiration. *European Journal of Soil Biology*, 47(4), 247-255.

901 Levin, I., Naegler, T., Kromer, B., Diehl, M., Francey, R. J., Gomez-Pelaez, A. J., et al. (2010). Observations and modelling of the global distribution and long-  
902 term trend of atmospheric (CO<sub>2</sub>)-C-14 (vol 62, pg 26, 2010). *Tellus Series B-Chemical and Physical Meteorology*, 62(3), 207-207.

903 Lin, G. H., Ehleringer, J. R., Rygielwicz, P. T., Johnson, M. G., & Tingey, D. T. (1999). Elevated CO<sub>2</sub> and temperature impacts on different components of soil  
904 CO<sub>2</sub> efflux in Douglas-fir terracosms. *Global Change Biology*, 5(2), 157-168.

905 Litton, C. M., Raich, J. W., & Ryan, M. G. (2007). Carbon allocation in forest ecosystems. *Global Change Biology*, 13(10), 2089-2109.

906 ~~Litton, C. M., Ryan, M. G., & Knight, D. H. (2004). Effects of tree density and stand age on carbon allocation patterns in postfire lodgepole pine. *Ecological  
907 Applications*, 14(2), 460-475. doi:10.1890/02-5291~~

908 Lopez-Ballesteros, A., Serrano-Ortiz, P., Kowalski, A. S., Sanchez-Canete, E. P., Scott, R. L., & Domingo, F. (2017). Subterranean ventilation of allochthonous  
909 CO<sub>2</sub> governs net CO<sub>2</sub> exchange in a semiarid Mediterranean grassland. *Agricultural and Forest Meteorology*, 234, 115-126.  
910 doi:10.1016/j.agrformet.2016.12.021

911 ~~Maseyk, K. S., Lin, T., Luysaert, S., Inglima, I., Jung, M., Richardson, A.D., Reichstein, M., Papale, D., et al. (2007). CO<sub>2</sub> balance of boreal, temperate, and  
912 tropical forests derived from a global database. *Glob. Change Biol.* 13, 2509-2537.~~

913 ~~Rotenberg, E., Gruenzweig, J. M., Schwartz, A., & Yakir, D. (2008b). Physiology-phenology interactions in a productive semi-arid pine forest. *New Phytologist*,  
914 178(3), 603-616.~~

915 Maseyk, K., Grünzweig, J. M., Rotenberg, E., & Yakir, D. (2008a). Respiration acclimation contributes to high carbon-use efficiency in a seasonally dry pine  
916 forest. *Global Change Biology*, 14(7), 1553-1567.

917 ~~Maseyk, K., Hemming, D., Angert, A., Leavitt, S. W., & Yakir, D. (2011). Increase in water use efficiency and underlying processes in pine forests across a  
918 precipitation gradient in the dry Mediterranean region over the past 30 years. *Oecologia*, 167(2), 573-585. doi:10.1007/s00442-011-2010-4~~

919 ~~Matteucci, M., Gruening, C., Ballarin, I. G., Seufert, G., & Cescatti, A. (2014). Soil and ecosystem carbon fluxes in a Mediterranean forest during and after  
920 drought. *Agrochimica*, 58, 91-115.~~

921 ~~Matteucci, M., Gruening, C., Ballarin, I. G., Seufert, G., & Cescatti, A. (2015). Components, drivers and temporal dynamics of ecosystem respiration in a  
922 Mediterranean pine forest. *Soil Biology & Biochemistry*, 88, 224-235. doi:10.1016/j.soilbio.2015.05.017~~

923 ~~Newell-Misson, L., Rocheteau, A., Rambal, S., Ourcival, J. M., Limousin, J. M., & Y., Fallon, R. D., Rodriguez, R. M. C., & Groene, L. C. (1985). INFLUENCE  
924 OF RAIN, TIDAL WETTING AND RELATIVE HUMIDITY ON RELEASE OF CARBON DIOXIDE BY STANDING DEAD SALT MARSH PLANTS.  
925 *Oecologia*, 68(1), 73-79. doi:10.1007/bf00379477~~

926 ~~Noh, N. J., Son, Y., Lee, S. K., Yoon, T. K., Seo, K. W., Kim, C., ... Hwang, J. (2010). InfluenceFunctional changes in the control of stand density on soil CO<sub>2</sub>  
927 efflux for carbon fluxes after 3 years of increased drought in a *Pinus densiflora* Mediterranean evergreen forest in Korea. *Journal of Plant Research*, 123(4),  
928 411-419. doi:10.1007/s10265-010-0331-8~~

929 [Ogee, J., Peylin, P., Cuntz, M., Bariac, T., Brunet, Y., Berbigier, P., et al. \(2004\). Partitioning net ecosystem carbon exchange into net assimilation and respiration](#)  
930 [with canopy scale isotopic measurements: An error propagation analysis with \(CO<sub>2</sub>\) C-13 and \(COO\) O-18 data. \*Global Biogeochemical Cycles\*, 18\(2\).](#)  
931 [Olsson, P., Linder, S., Giesler, R., & Hogberg, P. \(2005\). Fertilization of boreal forest reduces both autotrophic and heterotrophic soil respiration.? \*Global Change\*  
932 \[Biology\]\(#\), 11\(10\), 1745-1753. doi:10.1111/j.1365-2486.2009.02121.x](#)  
933 Pataki, D. E., Ehleringer, J. R., Flanagan, L. B., Yakir, D., Bowling, D. R., Still, C. J., et al. (2003). The application and interpretation of Keeling plots in terrestrial  
934 carbon cycle research. *Global Biogeochemical Cycles*, 17(1).  
935 Peterjohn, W. T., Melillo, J. M., Steudler, P. A., Newkirk, K. M., Bowles, F. P., & Aber, J. D. (1994). RESPONSES OF TRACE GAS FLUXES AND N  
936 AVAILABILITY TO EXPERIMENTALLY ELEVATED SOIL TEMPERATURES. *Ecological Applications*, 4(3), 617-625.  
937 Poulter, B., Frank, D., Ciais, P., Myneni, R. B., Andela, N., Bi, J., et al. (2014). Contribution of semi-arid ecosystems to interannual variability of the global carbon  
938 cycle. *Nature*, 509(7502), 600-+.

939 [Preisler, Y., Tatarinov, F., Grünzweig, JM, et al. \(2019\). Mortality versus survival in drought-affected Aleppo pine forest depends on the extent of rock cover and](#)  
940 [soil stoniness. \*Funct Ecol.\*: 00:1-12.](#)  
941 [Qubaja, R., Grünzweig, J., Rotenberg, E., & Yakir, D. \(2019\). Evidence for large carbon sink and long residence time in semi-arid forests based on 15-year flux](#)  
942 [and inventory records. Accepted for \*Global Change Biology\*](#)  
943 Raich, J. W., & Schlesinger, W. H. (1992). THE GLOBAL CARBON-DIOXIDE FLUX IN SOIL RESPIRATION AND ITS RELATIONSHIP TO VEGETATION  
944 AND CLIMATE. *Tellus Series B-Chemical and Physical Meteorology*, 44(2), 81-99.  
945 [Ramnarine, R., Wagner-Riddle, C., Dunfield, K. E., & Voroney, R. P. \(2012\). Contributions of carbonates to soil CO<sub>2</sub> emissions. \*Canadian Journal of Soil Science\*,](#)  
946 [92\(4\), 599-607. doi:10.4141/cjss2011-025](#)  
947 Raz-Yaseef, N., Rotenberg, E., & Yakir, D. (2010). Effects of spatial variations in soil evaporation caused by tree shading on water flux partitioning in a semi-arid  
948 pine forest. *Agricultural and Forest Meteorology*, 150(3), 454-462.  
949 Reichstein, M., Rey, A., Freibauer, A., Tenhunen, J., Valentini, R., Banza, J., et al. (2003). Modeling temporal and large-scale spatial variability of soil respiration  
950 from soil water availability, temperature and vegetation productivity indices. *Global Biogeochemical Cycles*, 17(4).  
951 Rey, A., Pegoraro, E., Tedeschi, V., De Parri, I., Jarvis, P. G., & Valentini, R. (2002). Annual variation in soil respiration and its components in a coppice oak  
952 forest in Central Italy. *Global Change Biology*, 8(9), 851-866.  
953 Roland, M., et al. (2012). Contributions of carbonate weathering to the net ecosystem carbon balance of a mediterranean forest. Thesis submitted to Antwerpen  
954 University, Antwerpen, Belgium.  
955 Ross, I., Misson, L., Rambal, S., Arneith, A., Scott, R. L., Carrara, A., et al. (2012). How do variations in the temporal distribution of rainfall events affect ecosystem  
956 fluxes in seasonally water-limited Northern Hemisphere shrublands and forests? *Biogeosciences*, 9(3), 1007-1024.  
957 [Rodeghiero M, Cescatti A. \(2005\). Main determinants of forest soil respiration along an elevation / temperature gradient in the Italian Alps. \*Glob Chang Biol\*](#)  
958 [11:1024-1041.](#)  
959 Rotenberg, E., & Yakir, D. (2010). Contribution of Semi-Arid Forests to the Climate System. *Science*, 327(5964), 451-454.  
960 [Ryan, M. G. \(1991\). EFFECTS OF CLIMATE CHANGE ON PLANT RESPIRATION. \*Ecological Applications\*, 1\(2\), 157-167.](#)  
961 [Ryan, M. G., & Law, B. E. \(2005\). Interpreting, measuring, and modeling soil respiration. \[Article\]. \*Biogeochemistry\*, 73\(1\), 3-27.](#)  
962 [Saleska, S. R., Harte, J., & Torn, M. S. \(1999\). The effect of experimental ecosystem warming on CO<sub>2</sub> fluxes in a montane meadow. \*Global Change Biology\*, 5\(2\),](#)  
963 [125-141.](#)  
964 [Scharlemann, J. P. W., Tanner, E. V. J., Hiederer, R., & Kapos, V. \(2014\). Global soil carbon: understanding and managing the largest terrestrial carbon pool. \*Carbon Management\*,](#)  
965 [5\(1\), 81-91.](#)  
966 Schiller, G. (2000), Ecophysiology of *Pinus halepensis* Mill. and *P. brutia* Ten, in *Ecology, Biogeography and Management of Pinus halepensis and P. brutia* Forest

967 Ecosystems in the Mediterranean Basin, edited by G. Ne'eman and L. Trabaud, pp. 51–65, Backhuys, Leiden, Netherlands.

968 ~~Schlesinger, W. H. (1982). CARBON STORAGE IN THE CALICHE OF ARID SOILS—A CASE STUDY FROM ARIZONA. *Soil Science*, 133(4), 247-255.~~

969 ~~Schulze, E. D. (2006). Biological control of the terrestrial carbon sink. *Biogeosciences*, 3(2), 147-166.~~

970 Serrano-Ortiz, P., Roland, M., Sanchez-Moral, S., Janssens, I. A., Domingo, F., Godderis, Y., & Kowalski, A. S. (2010). Hidden, abiotic CO<sub>2</sub> flows and gaseous

971 reservoirs in the terrestrial carbon cycle: Review and perspectives. *Agricultural and Forest Meteorology*, 150(3), 321-329. doi:10.1016/j.agrformet.2010.01.002

972 Shachnovich, Y., Berliner, P. R., & Bar, P. (2008). Rainfall interception and spatial distribution of throughfall in a pine forest planted in an arid zone. *Journal of*

973 *Hydrology*, 349(1-2), 168-177.

974 Shen, W. J., Jenerette, G. D., Hui, D. F., Phillips, R. P., & Ren, H. (2008). Effects of changing precipitation regimes on dryland soil respiration and C pool dynamics

975 at rainfall event, seasonal and interannual scales. *Journal of Geophysical Research-Biogeosciences*, 113(G3).

976 Subke, J.-A., Voke, N. R., Leronni, V., Garnett, M. H., & Ineson, P. (2011). Dynamics and pathways of autotrophic and heterotrophic soil CO<sub>2</sub> efflux revealed by

977 forest girdling. *Journal of Ecology*, 99(1), 186-193.

978 Taneva, L., & Gonzalez-Meler, M. A. (2011). Distinct patterns in the diurnal and seasonal variability in four components of soil respiration in a temperate forest

979 under free-air CO<sub>2</sub> enrichment. *Biogeosciences*, 8(10), 3077-3092.

980 Tang, J. W., Baldocchi, D. D., & Xu, L. (2005). Tree photosynthesis modulates soil respiration on a diurnal time scale. *Global Change Biology*, 11(8), 1298-1304.

981 Tatarinov, F., Rotenberg, E., Maseyk, K., Ogee, J., Klein, T., & Yakir, D. (2016). Resilience to seasonal heat wave episodes in a Mediterranean pine forest. *New*

982 *Phytologist*, 210(2), 485-496.

983 Taylor, A. J., Lai, C. T., Hopkins, F. M., Wharton, S., Bible, K., Xu, X. M., et al. (2015). Radiocarbon-Based Partitioning of Soil Respiration in an Old-Growth

984 Coniferous Forest. *Ecosystems*, 18(3), 459-470.

985 ~~Villegas, J. C., Dominguez, F., Barron Gafford, G. A., Adams, H. D., Guardiola Claramonte, M., Sommer, E. D., . . . Huxman, T. E. (2015). Sensitivity of regional~~

986 ~~evapotranspiration partitioning to variation in woody plant cover: insights from experimental dryland tree mosaics. *Global Ecology and Biogeography*, 24(9),~~

987 ~~1040-1048. doi:10.1111/geb.12349~~

988 Volcani, A., Karnieli, A., & Svoray, T. (2005). The use of remote sensing and GIS for spatio-temporal analysis of the physiological state of a semi-arid forest with

989 respect to drought years. *Forest Ecology and Management*, 215(1-3), 239-250. doi:10.1016/j.foreco.2005.05.063

990 ~~Wang, X., Liu, L. L., Piao, S. L., Janssens, I. A., Tang, J. W., Liu, W. X., . . . Xu, S. (2014). Soil respiration under climate warming: differential response of~~

991 ~~heterotrophic and autotrophic respiration. *Global Change Biology*, 20(10), 3229-3237. doi:10.1111/gcb.12620~~

992 Xu, M., & Qi, Y. (2001). Soil-surface CO<sub>2</sub> efflux and its spatial and temporal variations in a young ponderosa pine plantation in northern California. *Global*

993 *Change Biology*, 7(6), 667-677.

994 Xu, Z. F., Tang, S. S., Xiong, L., Yang, W. Q., Yin, H. J., Tu, L. H., . . . Tan, B. (2015). Temperature sensitivity of soil respiration in China's forest ecosystems:

995 Patterns and controls. *Applied Soil Ecology*, 93, 105-110. doi:10.1016/j.apsoil.2015.04.008

996 ~~Yakir, D., & Sternberg, L. D. L. (2000). The use of stable isotopes to study ecosystem gas exchange. *Oecologia*, 123(3), 297-311.~~

997 Yu, S. Q., Chen, Y. Q., Zhao, J., Fu, S. L., Li, Z., Xia, H. P., & Zhou, L. X. (2017). Temperature sensitivity of total soil respiration and its heterotrophic and

998 autotrophic components in six vegetation types of subtropical China. *Science of the Total Environment*, 607, 160-167. doi:10.1016/j.scitotenv.2017.06.194

999 ~~Zhao, Z. Y., Peng, C. H., Yang, Q., Meng, F. R., Song, X. Z., Chen, S. T., et al. (2017). Model prediction of biome specific global soil respiration from 1960 to~~

1000 ~~2012. *Earths Future*, 5(7), 715-729.~~

1001 Zhou, T., Shi, P. J., Hui, D. F., & Luo, Y. Q. (2009). Global pattern of temperature sensitivity of soil heterotrophic respiration (Q(10)) and its implications for

1002 carbon-climate feedback. *Journal of Geophysical Research-Biogeosciences*, 114.

1003 **7. Supporting Information**

1004 **Table S1-S1-1** | Monthly mean values of net ecosystem exchange (NEE), gross primary production (GPP), and ecosystem respiration (Re) and soil respiration (Rs)  
 1005 during study period. Note: the numbers in parenthesis is the  $\pm$ se.

Season	Month	NEE	GPP	Re	Rs
		[ $\mu\text{mol m}^{-2} \text{s}^{-1}$ ]			
<b>Wet season (Nov-Apr)</b>	Nov	-0.25 (0.10)	-0.81 (0.10)	0.56 (0.03)	0.78 (0.01)
	Dec	-0.48 (0.05)	-1.08 (0.04)	0.59 (0.01)	0.57 (0.01)
	Jan	-0.94 (0.11)	-1.96 (0.11)	1.02 (0.02)	0.91 (0.01)
	Feb	-1.52 (0.19)	-3.58 (0.20)	2.06 (0.03)	1.52 (0.02)
	Mar	-2.23 (0.17)	-4.65 (0.17)	2.42 (0.02)	1.54 (0.01)
	Apr	-1.32 (0.13)	-3.98 (0.13)	2.66 (0.02)	1.40 (0.01)
	<b>Average [<math>\mu\text{mol m}^{-2} \text{s}^{-1}</math>]</b>	<b>-1.12 (0.30)</b>	<b>-2.68 (0.66)</b>	<b>1.55 (0.38)</b>	<b>1.12 (0.17)</b>
	<b>Season sum [g C m<sup>-2</sup>]</b>	<b>-203 (9)</b>	<b>-482 (20)</b>	<b>279 (11)</b>	<b>202 (5)</b>
<b>Rs/Re [%]</b>				<b>72 (13)</b>	
<b>Dry season (May-Oct)</b>	May	-0.55 (0.08)	-2.23 (0.08)	1.67 (0.02)	1.20 (0.01)
	Jun	0.50 (0.04)	-0.90 (0.04)	1.40 (0.02)	0.61 (0.01)
	Jul	0.29 (0.04)	-0.77 (0.03)	1.06 (0.01)	0.36 (0.01)
	Aug	0.45 (0.05)	-0.63 (0.04)	1.08 (0.02)	0.24 (0.01)
	Sep	0.25 (0.04)	-0.60 (0.04)	0.85 (0.02)	0.30 (0.01)
	Oct	0.26 (0.03)	-0.50 (0.02)	0.76 (0.01)	0.30 (0.01)
	<b>Average [<math>\mu\text{mol m}^{-2} \text{s}^{-1}</math>]</b>	<b>0.20 (0.16)</b>	<b>-0.94 (0.26)</b>	<b>1.14 (0.14)</b>	<b>0.50 (0.15)</b>
	<b>Season sum [g C m<sup>-2</sup>]</b>	<b>36 (5)</b>	<b>-173 (8)</b>	<b>209 (4)</b>	<b>93 (5)</b>
<b>Rs/Re [%]</b>				<b>44 (7)</b>	
<b>Annual</b>	<b>Average (SE) [<math>\mu\text{mol m}^{-2} \text{s}^{-1}</math>]</b>	<b>-0.46 (0.26)</b>	<b>-1.81 (0.43)</b>	<b>1.34 (0.20)</b>	<b>0.8 (0.1)</b>
	<b>Annual sum (SE) [g C m<sup>-2</sup> y<sup>-1</sup>]</b>	<b>-167 (8)</b>	<b>-655 (13)</b>	<b>488 (6)</b>	<b>295 (4)</b>
	<b>Rs/Re [%]</b>				<b>60 (10)</b>

1006

1007 **Table S2SI-2** | Exponential and linear relationships between soil respiration rate (Rs;  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) and abiotic factors during 2015-2016. Ts ( $^{\circ}\text{C}$ ): soil temperature;  
 1008 SWC ( $\text{m}^3 \text{m}^{-3}$ ): soil water content; PAR ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ): incoming photosynthetic activity radiation above canopy. The best-fit model parameters ( $\beta_0$ ,  $\beta_1$ ,  $\beta_2$ , and  $\beta_3$ )  
 1009 are reported for each model together with the squared coefficient of regression ( $R^2$ ), and the root mean squared error (RSME).  
 1010

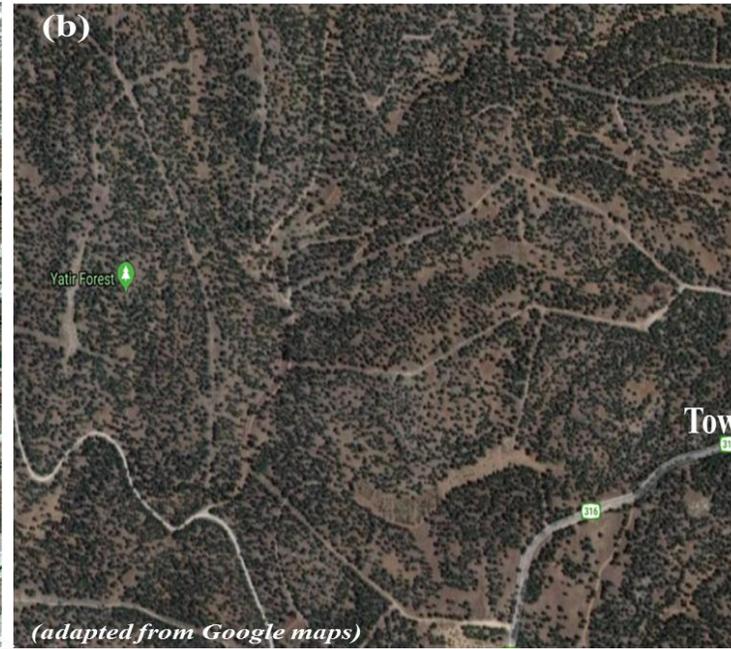
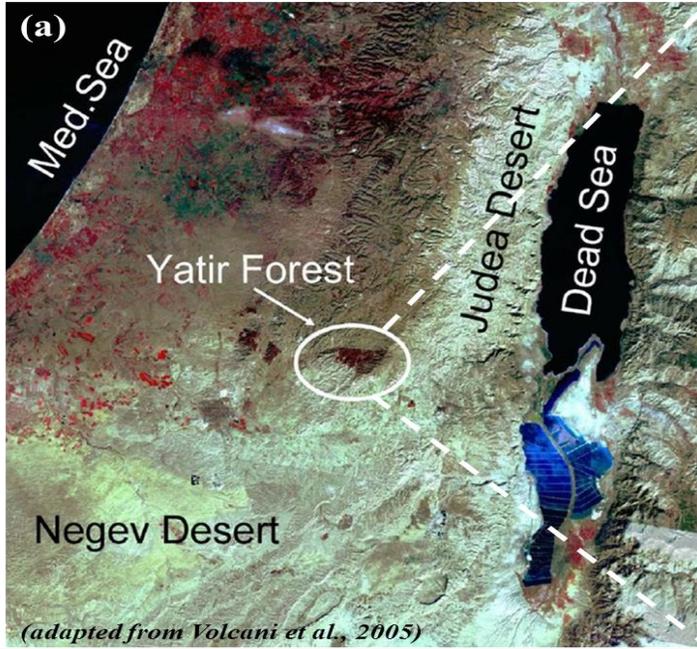
a) Up-scaled daily time series (the models that used during Grünzweig et al., 2009)

Model	Study	$\beta_0$	$\beta_1$	$\beta_2$	$\beta_3$	$\beta_4$	$R^2$
$\beta_0 + \beta_1\theta + \beta_2\text{PAR}$	2000-2006	-2.306	25.39	0.000545			0.83
$<0.2 \text{ m}^3 \text{H}_2\text{O m}^{-3} \text{soil}\theta$	2015-2016	-0.7313	11.14	0.000564			0.43
$\beta_0 + \beta_1 e^{\beta_2 \text{Ts}} + \beta_3 e^{\beta_4 \text{PAR}}$	2000-2006	1.394	0.1463	0.151	0.008408	0.003154	0.86
$<0.2 \text{ m}^3 \text{H}_2\text{O m}^{-3} \text{soil}\theta$	2015-2016						0.70

1011 b) Up-scaled half-hour time series

Model	$\beta_0$	$\beta_1$	$\beta_2$	$\beta_3$	$R^2$	SSE
$\beta_0 + \beta_1 \text{Ts}$	1.264	-0.02			0.07	0.556
$\beta_0 e^{\beta_1 \text{Ts}}$	1.309	-0.02			0.07	0.558
$\beta_0 + \beta_1 \theta$	0.2934	5.57			0.35	0.4667
$\beta_0 + \beta_1 \theta + \beta_2 \theta^2$	-0.2175	17.47	-48.35		0.42	0.4388
$e^{\beta_0 + \beta_1 \theta + \beta_2 \theta^2}$	-1.68	23.49	-67.3		0.44	0.4378
$\beta_0 + \beta_1 \text{PAR}$	0.7121	0.0002			0.05	0.5603
$\beta_0 + \beta_1 \theta + \beta_2 \text{Ts}$	-0.4213	7.626	0.02473		0.40	0.4499
$\beta_0 + \beta_1 \theta + \beta_2 \text{PAR}$	0.1162	5.989	0.00028		0.44	0.4295
$\beta_0 \beta_1^{((\text{Ts}-10)/10)} \theta \beta_2$	6.714	1.655	1.083		0.52	0.4151
$(\beta_0 / (1 + e^{\beta_1 * (\beta_2 - \text{Ts})})) * \theta \beta_3$	11.91	0.267	12.04	0.9908	0.54	0.3914
$(\beta_0 / (1 + e^{\beta_1 * (\beta_2 - \text{PAR})})) * \theta \beta_3$	90.12	0.0004	8625	0.6838	0.50	0.4169
$\beta_0 e^{\beta_1 \text{Ts}} e^{\beta_2 \theta + \beta_3 \theta^2}$	0.05126	0.04274	28.51	74.44	0.60	0.3932

1012

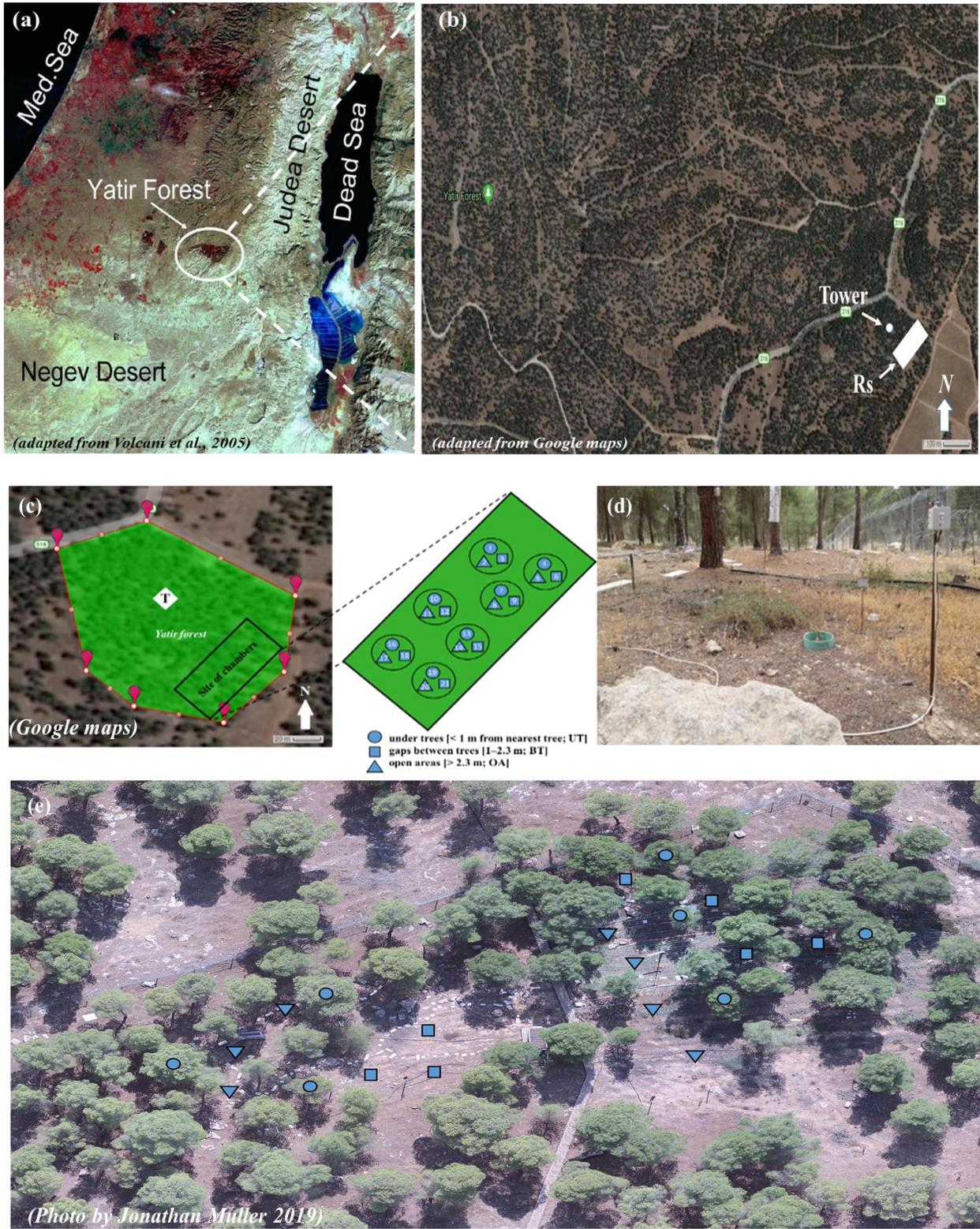


1013  
1014

1015 **Table SI-3** | Annual heterotrophic respiration (Rh), autotrophic respiration (Ra), soil respiration (Rs), ecosystem  
 1016 respiration (Re), gross primary productivity (GPP), net primary productivity (NPP), net ecosystem production (NEP; from  
 1017 eddy covariance), respectively. The relative contribution of Rh, and Ra and Rs to Re, and the ecosystem and soil carbon  
 1018 sequestration efficiency as CSE (NEP/GPP) and SCSE ( $\Delta C_{\text{soil}}/\text{GPP}$ ), where  $\Delta C_{\text{soil}}$  is the annual change of soil carbon.

<u>Study</u>	<u>Rh</u>	<u>Ra</u>	<u>Rs</u>	<u>Re</u>	<u>GPP</u>	<u>NPP</u>	<u>NEP</u>	<u>Rh/Re</u>	<u>Ra/Re</u>	<u>Rs/Re</u>	<u>CSE</u>	<u>SCSE</u>
	<u>[g m<sup>-2</sup> y<sup>-1</sup>]</u>							<u>[%]</u>			<u>[%]</u>	
<b>Semi-arid<sup>1</sup></b>	115	312	295	488	655	282	167	23	64	60	25	8.7
<b>Europe, mean</b>	368	589	657	957	1107	518	150	38	62	69	14	1.8
<b>Europe<sup>EN</sup>, mean</b>	461	657	381	1117	1475	818	358	41	59	74	24	1.4
<b>Boreal, global</b>	301	561	411	862	982	381	116	35	65	48	12	0.7
<b>Temperate, global</b>	420	730	773	1150	1461	669	306	37	64	67	21	1.4
<b>Tropical, global</b>	877	2184	1412	3061	3351	864	403	29	71	46	12	0.3

1019 <sup>1</sup> This study from November 2015 to October 2016. <sup>EN</sup> Evergreen needleleaf forests. References for all other vegetation  
 1020 types appear in the SI.



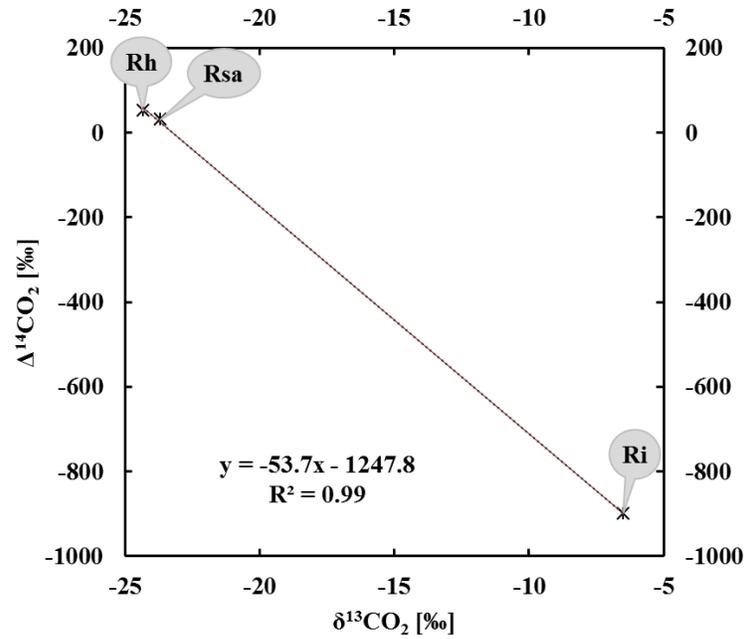
1021

1022

1023

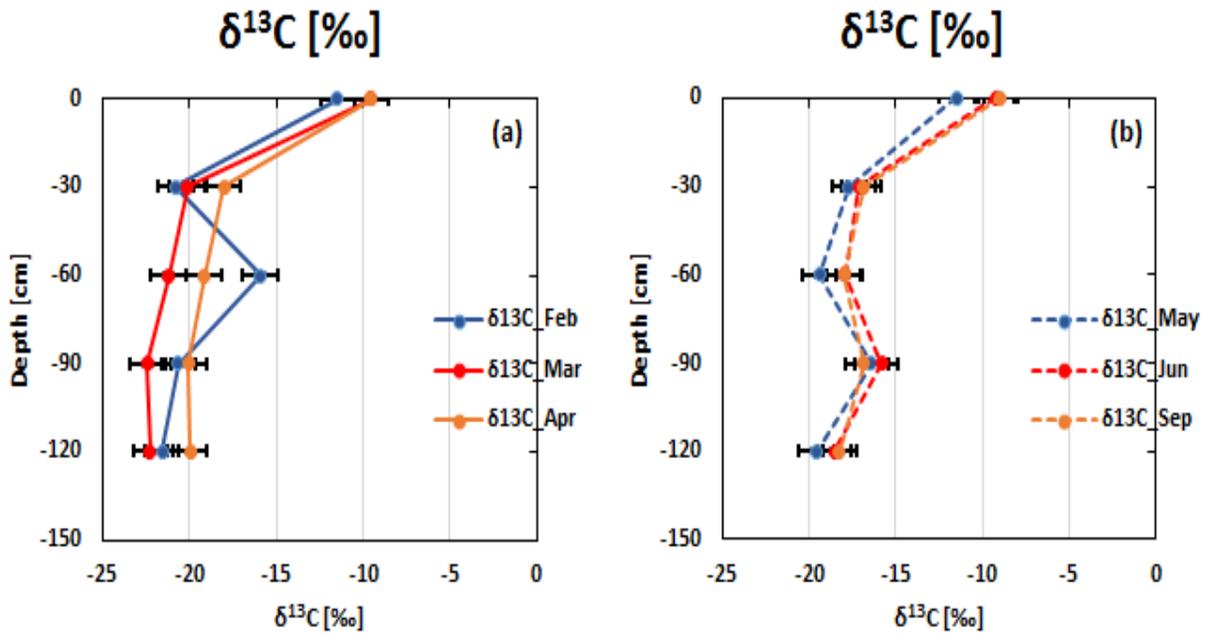
**Figure S4SI-1** | (a) Landsat-TM image of Central Israel. (b) Map of the experimental set-up at the *Pinus halepensis*

1024 Yatir forest with white rectangle site of soil respiration (Rs) measurements and white dot is the location of the eddy  
 1025 covariance tower (NEE-), c, d, and e) Photographs showing conditions of locations, site, and the schematic diagrams  
 1026 describing experiment design.

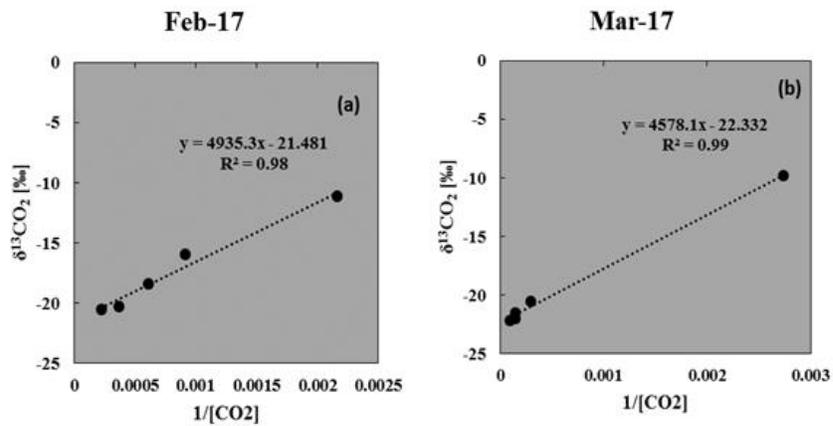


1027 **Figure S2SI-2** | The linear regression line used to estimate the  $\Delta^{14}\text{C}$  of Rs. The line (dotted) was produced by the  
 1028 correlation between the average of the measured  $\delta^{13}\text{C}$  values of Rsa, Rsh, and the  $\delta^{13}\text{C}$  Ri (all from incubation  
 1029 measurements), and the  $\Delta^{14}\text{C}$  values estimated based on measured  $\Delta^{14}\text{C}$  at our site (Carmi et al. 2013) adjusted to the  
 1030 present study period and the mean accepted ages of autotrophic and heterotrophic soil organic material (Graven et al.,  
 1031 2012; Levin et al., 2010; Taylor et al., 2015).  
 1032

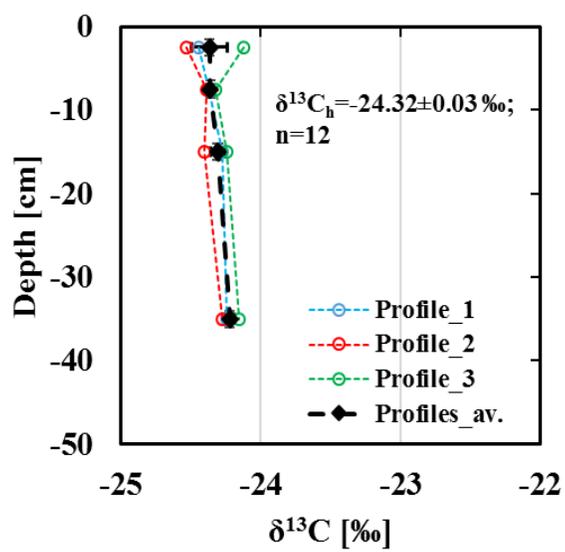
1033



1034  
 1035 **Figure S3SI-3** | Monthly averages of  $\delta^{13}\text{C}$  (‰) from the soil  $\text{CO}_2$  profile (at 0, 30, 60, 90, and 120 cm soil depth)  
 1036 during some campaigns in 2016 to determine the seasonal variations in the relative contribution of soil autotrophic (Rsa),  
 1037 heterotrophic (Rh), and abiotic (Ri) components to Rs.



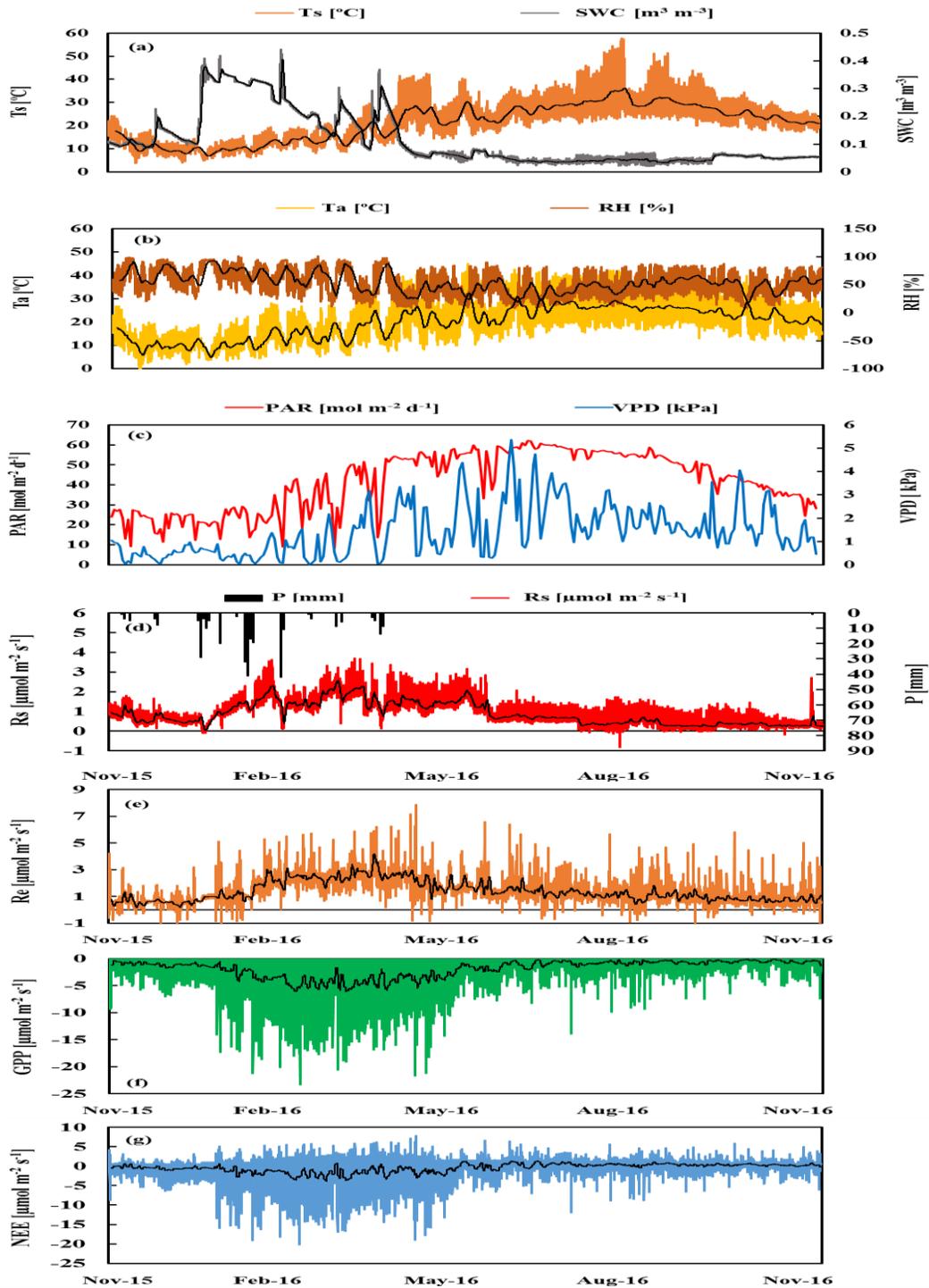
1038  
 1039 **Figure S4SI-4** | Keeling plot for soil  $\text{CO}_2$  profile (at 0, 30, 60, 90, and 120 cm soil depth) during some campaigns in  
 1040 2016 to determine the seasonal variations in the relative contribution of soil autotrophic (Rsa), heterotrophic (Rh), and  
 1041 abiotic (Ri) components to Rs.



1042  
1043  
1044  
1045

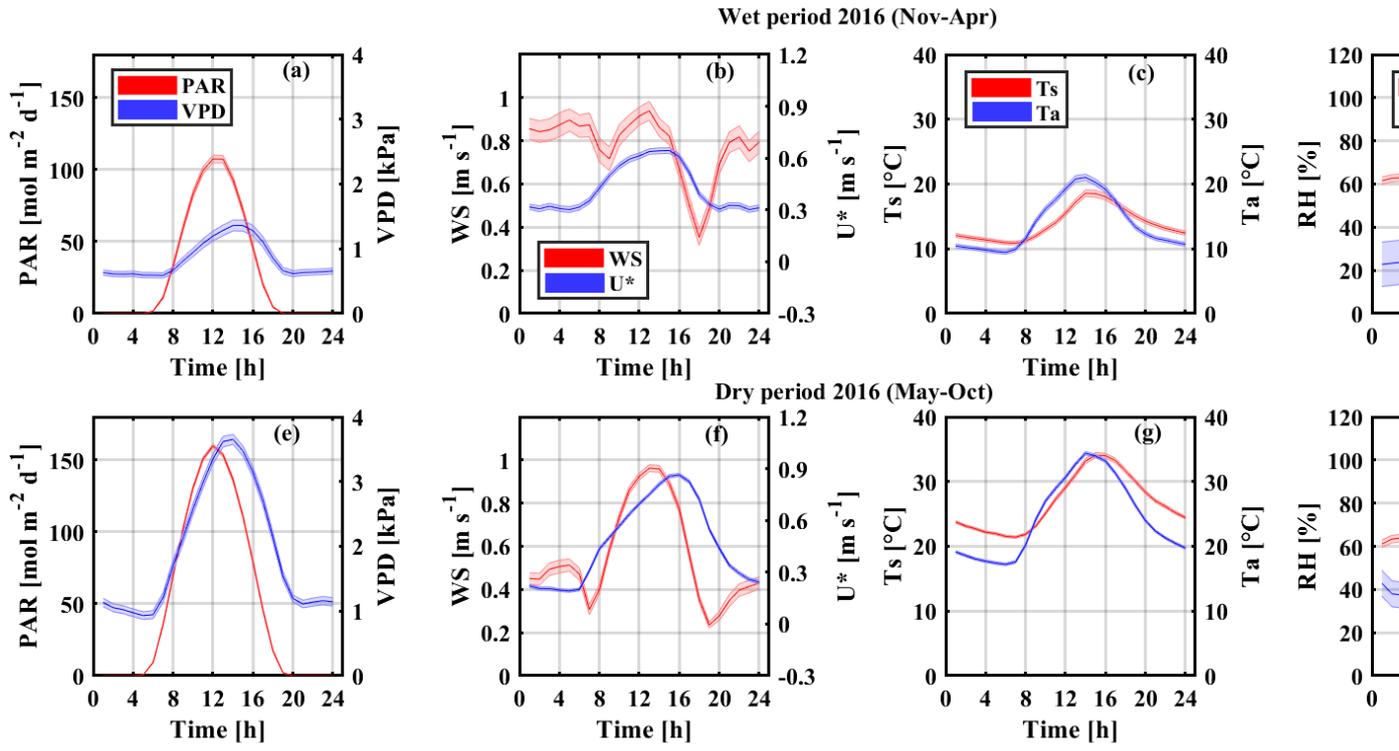
**Figure SI-5** |  $\delta^{13}C$  of soil organics profile with depth (at 0-5, 5-10, 10-20, and 20-50 cm soil depth) from three sites during some campaigns in 2016 to determine the relative contribution of soil heterotrophic (Rh) to Rs (STDEV of the 12 samples = 0.12‰).

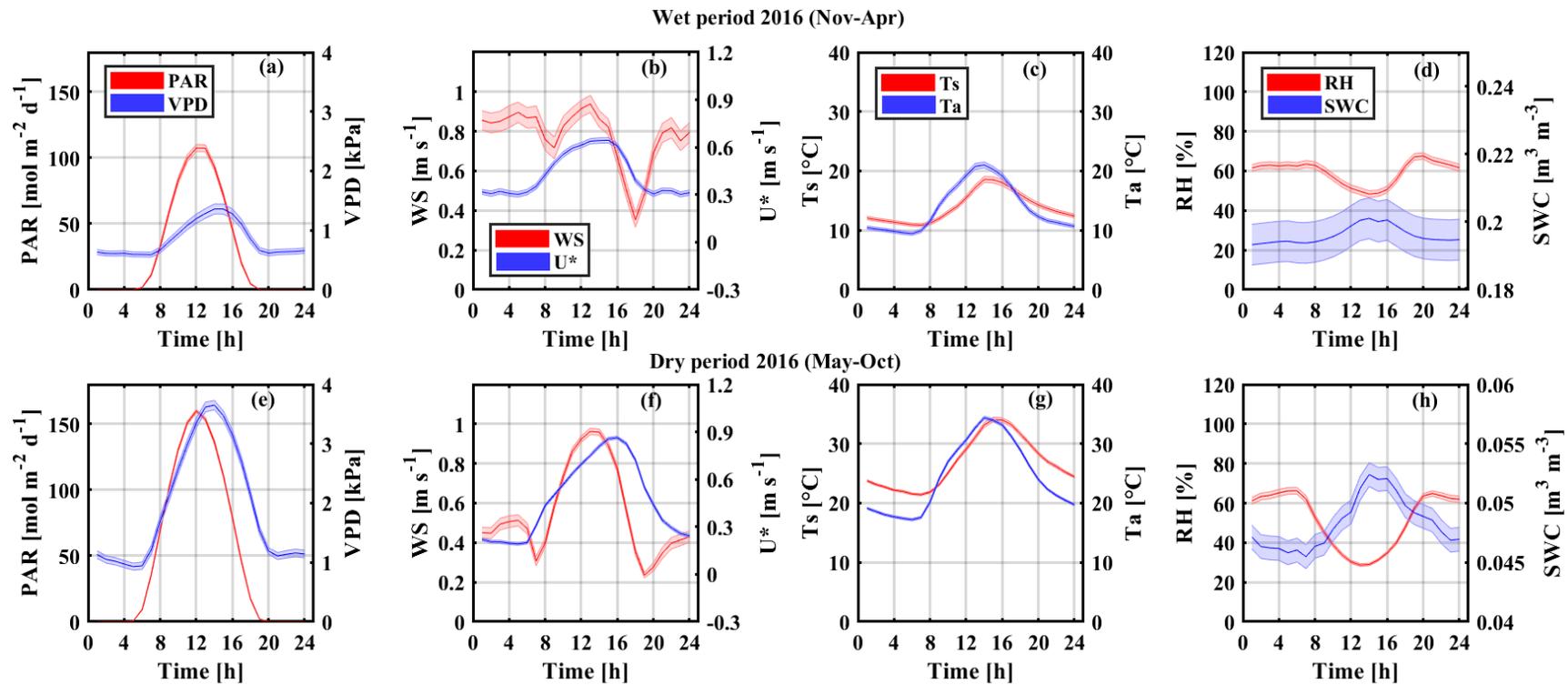
1046  
1047  
1048  
1049  
1050  
1051  
1052  
1053  
1054  
1055  
1056  
1057



**Figure S5SI-6** | a) half-hour values for soil temperature 5 cm ( $T_s$ ) and soil water content 10 cm ( $SWC_{0-10cm}$ ), b) half-hour values for the air temperature at 20 cm ( $T_a$ ) and relative humidity at 20 cm (RH), c) daily average of incoming photosynthetic activity radiation above canopy (PAR) and vapour pressure deficit (VPD), half-hour values for the following CO<sub>2</sub> fluxes d) up-scaled  $R_s$ , e) ecosystem respiration (Re), f) gross primary production (GPP), and g) net ecosystem exchange (NEE). Black lines are a running average lines for a widows of 2 days.



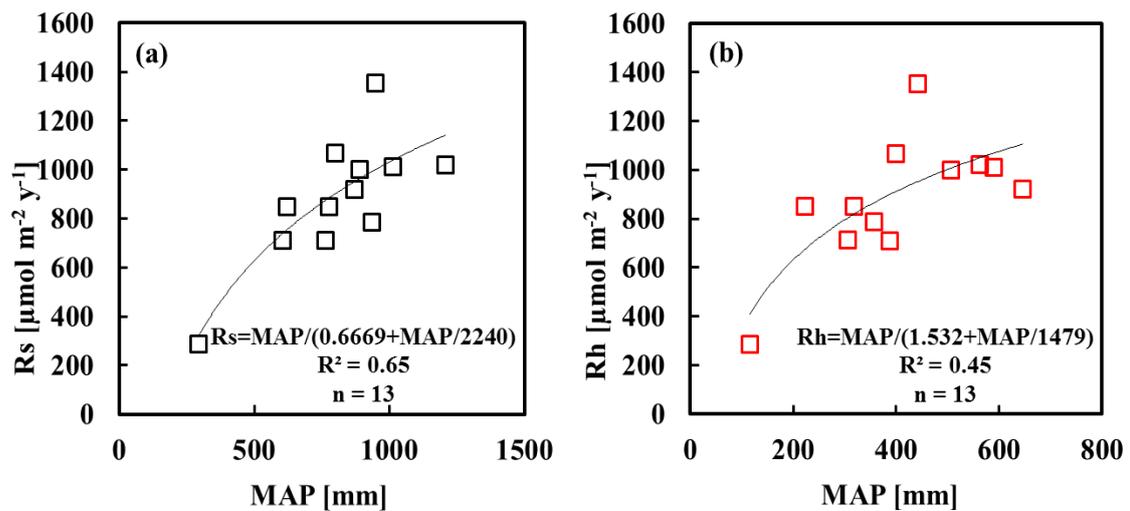




1060

1061  
1062  
1063  
1064

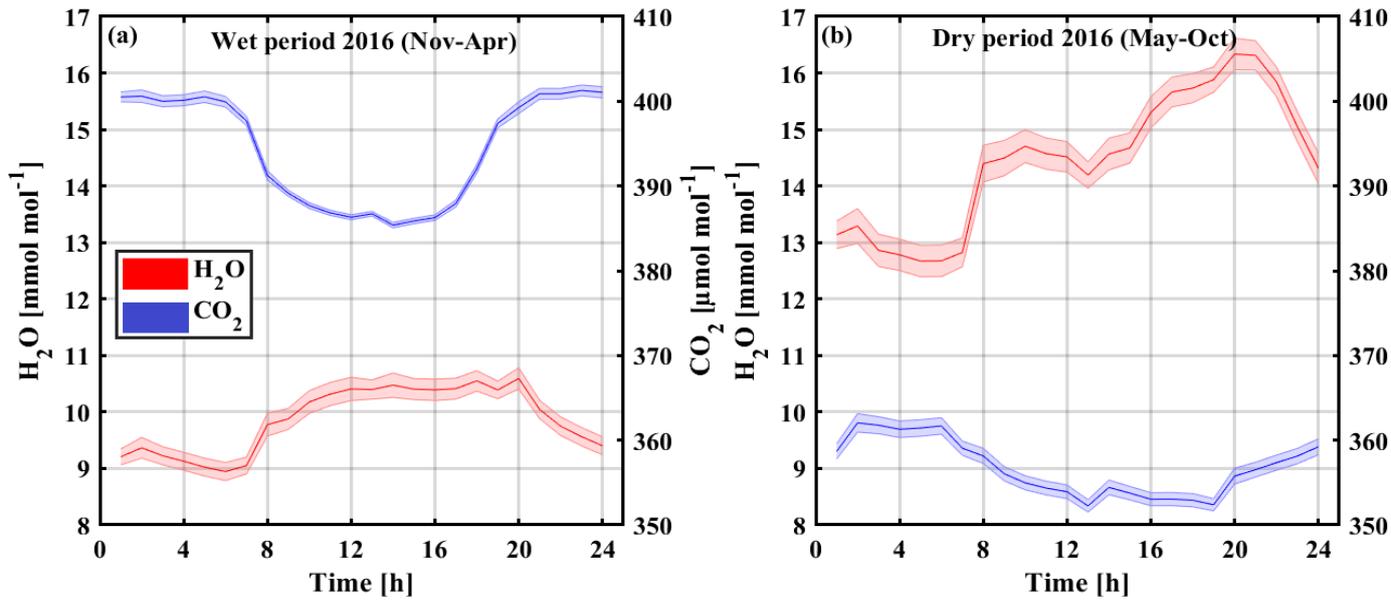
**Figure S6SI-7** | Typical diurnal cycle of the meteorological parameters during the wet period (Nov.-Apr.; upper panels) and for the dry period (May-Oct.; lower panels); each set includes six months of half-hour measurements. a and e) incoming photosynthetic activity radiation above canopy (PAR) and vapour pressure deficit (VPD), b and f) wind speed (WS) and covariation of friction velocity ( $U^*$ ), c and g) soil temperature at 5 cm ( $T_s$ ) and air temperature at 20 cm ( $T_a$ ), and d and h) relative humidity (RH) and soil water content at the top 10 cm (SWC0-10cm). Shaded areas indicate  $\pm se$ .



**Figure SI-8** | An asymptotic function based on the Michaelis-Menten equation (Kool et al., 2007) was fit to a)  $R_s$  or b)  $R_h$  vs. MAP from the European Evergreen needleleaf data as follows:  $R_s = \text{MAP}/(0.6669 + \text{MAP}/2240)$ ,  $R^2 = 0.65$ ,  $p < 0.01$ ,  $n=13$  (Flechar et al., 2019a).

### Supplementary References (used for data in Table SI-3)

1. [Etzold, S., Ruehr, N., Zweifel, R., Dobbertin, M., Zingg, A., Pluess, P., et al. \(2011\). The Carbon Balance of Two Contrasting Mountain Forest Ecosystems in Switzerland: Similar Annual Trends, but Seasonal Differences. \*Ecosystems\*, 14\(8\), 1289-1309.](#)
  2. [Flechar, C. R., Ibrom, A., Skiba, U. M., de Vries, W., van Oijen, M., Cameron, D. R., et al. \(2019\). Carbon/nitrogen interactions in European forests and semi-natural vegetation. Part I: Fluxes and budgets of carbon, nitrogen and greenhouse gases from ecosystem monitoring and modelling, \*Biogeosciences Discuss.\*, <https://doi.org/10.5194/bg-2019-333>, in review, 2019.](#)
  3. [Flechar, C. R., van Oijen, M., Cameron, D. R., de Vries, W., Ibrom, A., Buchmann, N., Dise, N. B., et al. \(2019\). Carbon/nitrogen interactions in European forests and semi-natural vegetation. Part II: Untangling climatic, edaphic, management and nitrogen deposition effects on carbon sequestration potentials, \*Biogeosciences Discuss.\*, <https://doi.org/10.5194/bg-2019-335>, in review, 2019.](#)
  4. [Hursh, A., Ballantyne, A., Cooper, L., Maneta, M., Kimball, J., & Watts, J. \(2017\). The sensitivity of soil respiration to soil temperature, moisture, and carbon supply at the global scale. \*Global Change Biology\*, 23\(5\), 2090-2103. doi:10.1111/gcb.13489](#)
  5. [Schulze, E. D., Luyssaert, S., Ciais, P., Freibauer, A., Janssens, I. A., Soussana, J. F., et al. \(2009\). Importance of methane and nitrous oxide for Europe's terrestrial greenhouse-gas balance. \*Nature Geoscience\*, 2\(12\), 842-850.](#)
  6. [Avitabile, V., & Camia, A. \(2018\). An assessment of forest biomass maps in Europe using harmonized national statistics and inventory plots. \*Forest Ecology and Management\*, 409, 489-498.](#)
  7. [De Vos, B., Cools, N., Ilvesniemi, H., Vesterdal, L., Vanguelova, E., & Camicelli, S. \(2015\). Benchmark values for forest soil carbon stocks in Europe: Results from a large scale forest soil survey. \*Geoderma\*, 251, 33-46.](#)
  8. [Luyssaert, S., Inglima, I., Jung, M., Richardson, A. D., Reichstein, M., Papale, D., et al. \(2007\). CO2 balance of boreal, temperate, and tropical forests derived from a global database. \*Global Change Biology\*, 13\(12\), 2509-2537.](#)
- [Pan, Y. D., Birdsey, R. A., Fang, J. Y., Houghton, R., Kauppi, P. E., Kurz, W. A.,](#)



1100

1101

1102

1103

**Figure S7** | Representative diurnal cycles of the ambient H<sub>2</sub>O and CO<sub>2</sub> concentrations at ground level during a) the wet (Nov-Apr) and b) the dry (May-Oct) periods, each set includes six months of half hour measurements. These concentrations were measured with the system that determined R<sub>s</sub>; shaded areas indicate ±se.

1104

1105

1106

1107

1108

1109

1110

[14.9. et al. \(2011\). A Large and Persistent Carbon Sink in the World's Forests. Science, 333\(6045\), 988-993.](#)