Heat and drought events alter biogenic capacity to balance CO2 budget in south-western Europe

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Abstract

Heat and drought events are increasing in frequency and intensity, posing significant risks to natural and agricultural areas with uncertain effects on the net ecosystem CO2 exchange (NEE). We modified the Vegetation Photosynthesis and Respiration Model to include soil moisture impacts on the gross ecosystem exchange (GEE) and respiration (RECO) fluxes and determine the temporal variability of NEE over south-western Europe for 2001-2022. Warming temperatures lengthen growing seasons causing an increase in GEE which is mostly compensated by a similar increment in RECO, resulting in a modest annual increase of net carbon sink of 0.80 gC/m2year but with high spatial and annual variability. The heatwave of 2022 reduced NEE by 78.5 TgC, a 27% decrease from the mean. The interannual variability is more influenced by drought in temperate humid regions than in Mediterranean semi-arid regions. These results emphasize the vulnerability of the net carbon sink as drying trends could revert the NEE trends, as it is happening for croplands in the French Central Massif.

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Heat and drought events alter biogenic capacity to balance CO₂ budget in south western Europe

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22 Key Points:

- We modify the Vegetation Photosynthesis and Respiration Model to include soil moisture
 impacts on ecosystem carbon fluxes.
- A modest annual increase of net cabon sink of 0.80 gC/m²year is found in south-western
 Europe but with high spatial and annual variability.
- The interannual net ecosystem exchange variability is more influenced by drought in temperate humid regions than in Mediterranean semi-arid regions.
- The heatwave and drought event of 2022, reduced net ecosystem exchange by 78.5 TgC,
- 30 a 27% decrease from the mean.

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32 Abstract

Heat and drought events are increasing in frequency and intensity, posing significant risks to 33 34 natural and agricultural areas with uncertain effects on the net ecosystem CO_2 exchange (NEE). We modified the Vegetation Photosynthesis and Respiration Model to include soil moisture 35 36 impacts on the gross ecosystem exchange (GEE) and respiration (R_{FCO}) fluxes and determine the temporal variability of NEE over south-western Europe for 2001-2022. Warming temperatures 37 38 lengthen growing seasons causing an increase in GEE which is mostly compensated by a similar increment in R_{ECO}, resulting in a modest annual increase of net carbon sink of 0.80 gC/m²year 39 40 but with high spatial and annual variability. The heatwave of 2022 reduced NEE by 78.5 TgC, a 27% decrease from the mean. The interannual variability is more influenced by drought in 41 42 temperate humid regions than in Mediterranean semi-arid regions. These results emphasize the vulnerability of the net carbon sink as drying trends could revert the NEE trends, as it is 43 happening for croplands in the French Central Massif. 44

45 **1 Introduction**

46 Global Global climate change and the increasing occurrence of extreme climate events are profoundly impacting the terrestrial carbon balance, altering vegetation dynamics, and 47 48 influencing the net carbon uptake from ecosystems (Ciais et al., 2005; Keenan et al., 2016; Reichstein et al., 2013). Climate warming has extended the growing season in Northern 49 ecosystems by producing more favorable conditions for photosynthesis, thereby increasing their 50 terrestrial ecosystem productivity or gross ecosystem exchange (GEE) (Ciais et al., 2019; Zhu et 51 52 al., 2016). The increased atmospheric carbon dioxide (CO₂) concentrations also have positive fertilization effects on the vegetation productivity (Los, 2013; Schimel et al., 2015; Thornton et 53 al., 2007). However, warming has also stimulated the release of terrestrial carbon to the 54 atmosphere or ecosystem respiration (R_{ECO}), by enhanced soil organic matter decomposition and 55 vegetation respiration (Keenan et al., 2016). Interannual variations of biogenic carbon fluxes are 56 expected to increase with increasing frequency and intensity of extreme climate events 57 (Zscheischler, Mahecha, et al., 2014; Zscheischler, Reichstein, et al., 2014), potentially 58 destabilizing the long-term carbon cycle (Fernández-Martínez et al., 2023). These trends depend 59 on vegetation and local climate. For example, arid and semi-arid regions, such as the southern 60 Iberian Peninsula and northern Africa, present higher interannual variations of GEE (Zhang et 61

al., 2016). On the other hand, GEE in humid benefit from the CO₂ fertilization and the longer
growing seasons in high latitudes responsible for larger GEE trends compared to other regions
(Zhang et al., 2016).

There is an urgent need to better understand how warming and drying trends affect the 65 vegetation in transition regions like south-western Europe. Recent studies have focused on 66 southern Europe, one of the key regions impacted by climate change (Giorgi & Lionello, 2008), 67 with an increasing frequency and intensity of heat and drought events (Fischer & Schär, 2010; 68 Molina et al., 2020). Over the last two decades, observable impacts have been observed 69 70 (Barriopedro et al., 2011; Vicente-Serrano et al., 2014), which pose significant risks to crops and natural ecosystems. Although the Mediterranean climate is typically characterized by long dry 71 summers (Gilabert et al., 2015), the resilience of its forests (Gazol et al., 2018) reaches its limits 72 when long drought episodes combined with heat waves start to affect the vegetation, leading to a 73 74 reduction of the net atmospheric CO₂ capture by the ecosystems or net ecosystem exchange (NEE). It is crucial to comprehend the impact of heat and drought events on the south-western 75 76 European carbon balance.

77 In recent years, the south-western European region has faced a series of droughts and hot 78 episodes. In France and Central Europe, air temperatures during the summer 2003 were the highest in the last 500 years, which caused a reduction of the continental net carbon uptake in the 79 range of 20 - 500 TgC year⁻¹, and in some regions changing the ecosystems from carbon sinks to 80 carbon sources (Ciais et al., 2005; Reichstein et al., 2007). The Iberian Peninsula experienced 81 82 droughts in 2004/2005, 2012, 2015, 2017 and 2022, which produced detrimental effects on the ecosystems, and combined with high summer temperatures intensified the occurrence of fires in 83 the territory (Ermitão et al., 2021; Faranda et al., 2023; Ionita et al., 2017; Nunes et al., 2019; 84 Sánchez-Benítez et al., 2018). In Italy, the summers of 2003, 2017 and 2022 with exceptional 85 temperatures which combined with persistent soil water deficits, resulted into extreme impacts 86 on vegetation productivity (Faranda et al., 2023; Rita et al., 2020; Trucchia et al., 2022). The 87 exceptional drought of the summer 2022, affecting central and south-eastern Europe, caused a 88 reduction of the net biosphere uptake in summer between 56 and 62 TgC over the drought area 89 90 (van der Woude et al., 2023). While different studies have investigated the role of water and heat 91 stress on GEE in southern Europe (Ermitão et al., 2021; Gilabert et al., 2015; Gouveia et al., 92 2017; Rita et al., 2020), changes in the net ecosystem exchange remains highly uncertain due to

complex dependencies from heat and drought episodes on ecosystem respiration R_{ECO} (Reichstein et al., 2013; von Buttlar et al., 2018).

While the impact of heat and drought events on the carbon balance has been well studied 95 for central and northern Europe (Bastos et al., 2020; Ciais et al., 2005; Ramonet et al., 2020), a 96 multi-year analysis for south-western Europe is lacking. South-western Europe has less long-97 term observational records of CO₂ concentrations and fluxes, which constrains the understanding 98 of regional biogenic carbon dynamics. Additionally, soil water availability and vapor pressure 99 100 deficit (atmospheric dryness) are the main factors driving interannual variability of 101 photosynthesis (Gilabert et al., 2015), but the timing of drought and heat events are also important factors in the vegetation response (Jin et al., 2023). Moreover, process-based 102 biogeochemical models usually fail at capturing the vegetation carbon response to extreme 103 variations in soil moisture (Stocker et al., 2018, 2019). 104

105 Remote sensing data-driven biosphere models, which estimate ecosystem fluxes based on satellite vegetation indices and meteorological drivers, usually estimate the water stress effect on 106 GEE using satellite sensed water indices or the vapor pressure deficit without considering soil 107 108 moisture as a model input (Fu et al., 2022; Stocker et al., 2018, 2019). Although satellite indices 109 can capture to some extent the effect of droughts on GEE (Maselli et al., 2009), they tend to underestimate the magnitude of GEE reductions under dry conditions (Stocker et al., 2019). For 110 instance, the Vegetation Photosynthesis and Respiration Model (VPRM) (Mahadevan et al., 111 2008) does not consider soil moisture as a driver (Mahadevan et al., 2008). Different studies 112 113 have shown the potential of enhancing the VPRM model capabilities by model parameters optimization (Dayalu et al., 2018) or by modifying the respiration equation (Gourdji et al., 2022), 114 resulting in similar or even better model performances compared to more complex process-based 115 models. 116

The main objective of this study is to determine the effect of heat and drought events on the temporal variability of the net biogenic carbon fluxes over south-western Europe, including Portugal, Spain, southern France, and Italy. To do so, we modify the VPRM model to represent the impact of soil moisture on the GEE and R_{ECO} for the period 2001-2022. In addition to the analysis of long-term carbon fluxes variability over this whole period we also study the control of climate driver anomalies (temperature, soil moisture and solar radiation) and drought indices

as the Standardized Precipitation Evaporation Index (SPEI) (Vicente-Serrano et al., 2010, 2013) 123 on the carbon fluxes interannual anomalies over ten biogeographical regions (Figure 1). To 124 complement the analysis of VPRM simulations, we also estimate GEE based on the sun-induced 125 chlorophyll fluorescence (SIF) provided by the Global Orbiting Carbon Observatory-2 (OCO-2) 126 SIF product (GOSIF) (Li & Xiao, 2019). Finally, we also study the intra-annual variations in 127 carbon fluxes during three exceptional heat and drought events: Western Europe region in the 128 year 2003, the Iberian sclerophyllous region in the year 2005, and the Atlantic region in the year 129 2022. 130





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135 2 Materials and Methods

136 **2.1 Study area**

- 137 The study region encompasses south-western Europe from Portugal to Italy (Figure 1). This large
- area presents a great diversity of ecosystems, topographical features, climates, land-uses, and soil

typologies (Gouveia et al., 2017), which we classify into 10 biogeographical regions based on the map of Terrestrial Ecoregions of the World from the World Wildlife Fund (Olson et al., 2001). The prevailing climate is the subtropical Mediterranean climate, with hot and dry summers, although other climates are present such as temperate oceanic (Atlantic part of France, north of Portugal and Spain), mountainous (high-altitude regions of the Alps, Pyrenees, and Dinaric Alps) and humid continental (Central Europe and north-eastern Italy) climates.

145 **2.2 VPRM modifications**

VPRM simulates surface CO_2 exchanges between the atmosphere and the biosphere using meteorological data and remote-sensing vegetation indices (cf. Supporting information). NEE is estimated as the difference between R_{ECO} and GEE, following a negative sign convention where negative fluxes represent CO_2 uptake by ecosystems. VPRM parameters are optimized for 8 plant functional types (PFT) representing various land cover types (i.e. evergreen, deciduous, mixed forest, shrubland, Mediterranean savanna, cropland, grassland, and sparsely vegetated), weighted by fractional coverage to calculate the regional ecosystem fluxes.

To account for the impact of soil moisture on GEE and R_{ECO} , modifications were made in the VPRM equations, with an R_{ECO} parameterization based on (Migliavacca et al., 2011). The methodology for optimizing the modified VPRM parameters and the evaluation using data from southern Europe flux tower observations is presented in the Supporting information.

The GEE parameterization consists of a light-use-efficiency approach that relates the GEE to the fraction of photosynthetically active radiation that is absorbed by the vegetation, combined with a set of optimized scaling factors (λ_{SW} , T_{scale} , W_{scale} and P_{scale}). We introduce a new scaling factor, SM_{scale} , to better represent soil moisture stress on GEE, distinguishing between energy-limited (adequate soil water) and water-limited regimes (insufficient soil water), according to (Stocker et al., 2019). The GEE parameterization is defined as:

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$$GEE = \lambda_{SW} \cdot T_{scale} \cdot W_{scale} \cdot P_{scale} \cdot SM_{scale} \cdot \frac{SW}{(1+SW/SW_0)} \cdot EVI$$
(1)

with *SW*, shortwave radiation, *SW*₀, the half-saturation shortwave radiation, and *EVI*, the enhanced vegetation index. The function SM_{scale} is defined to be 1 when the soil moisture (θ) is above a critical soil moisture threshold (θ^*) and decreases linearly below this threshold (Fu et al., 2022). Soil moisture in the uppermost soil level (0-15 cm depth), is normalized between the permanent wilting point and the field capacity of the soil. The form of the *SM*_{scale} function is:

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$$SM_{scale} = \begin{cases} q \cdot (\theta - \theta^*) + 1, \ \theta < \theta^* \\ 1, \ \theta \ge \theta^* \end{cases}$$
(2)

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where q and θ^* are optimized parameters. With this modification, we increase the number of parameters in the GEE parameterization from two (λ_{SW} , SW_0) to four (adding q and θ^*).

The default VPRM employs a linear function of air temperature to determine R_{ECO}. In 173 this study, we use an equation proposed in (Reichstein et al., 2003) and (Migliavacca et al., 174 2011). In our approach, we employ soil moisture, represented by a hyperbolic tangent function, 175 to depict water stress on R_{ECO}, rather than precipitation. This choice is due to soil moisture's 176 superior role in influencing both autotrophic and heterotrophic respirations, driving soil 177 microbial processes and plant stress (W. Liu et al., 2009). The R_{ECO} equation in the modified 178 VPRM relies on air temperature, soil moisture and short-term vegetation productivity (daily 179 GEE) as follows: 180

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$$R_{ECO} = (R_0 + k_1 \cdot GEE) \cdot tanh(k_2 \cdot \theta + \gamma) \cdot e^{E_0 \cdot \left(\frac{1}{T_{ref} - T_0} - \frac{1}{T - T_0}\right)}$$
(3)

GEE represents the average GEE over the previous 24 hours, and T is the air temperature. T_{ref} 182 and T_0 are fixed temperatures at 288.15 K (15 °C) and 227.13 K (-46.02 °C), respectively. 183 Model-specific constants, R_0 , k_1 , k_2 , γ and E_0 vary for each PFT and refer to reference abiotic 184 ecosystem respiration, sensitivity of ecosystem respiration to GEE, sensitivity of the ecosystem 185 186 to soil moisture, a constant indicating how R_{ECO} responds to null θ , and the activation energy parameter for the sensitivity of R_{ECO} to air temperature, respectively. Including vegetation 187 productivity in the respiration parameterization enhances the spatial and temporal dynamics of 188 189 R_{ECO}, preventing a bias in seasonal amplitude (Migliavacca et al., 2011). Air temperature influences R_{ECO} with non-linear dependencies (Jolly et al., 2005; Reichstein et al., 2003), which 190 can be represented using an Arrhenius type equation, as employed in this parameterization. 191

The VPRM model is used to estimate biogenic carbon fluxes (NEE, GEE and R_{ECO}) at an hourly resolution spanning from 2001 to 2022 at a spatial resolution of 9 km. The model uses meteorological drivers from the ERA5-Land dataset (Muñoz-Sabater, 2019) and satellite vegetation indices processed from MODIS surface reflectances (Vermote, 2015). The model computes fluxes individually for each PFT and results were subsequently aggregated based on VPRM PFT map. Another modification to VPRM includes differentiating between summer and winter crops within the cropland PFT, as it is explained in the Supporting information.

199 2.3 Climate and remotely sensed data

Climatic driver data for the VPRM model are from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5-Land reanalysis product. These data cover the years 202 2001 to 2022, with hourly frequency and 0.10 resolution (Muñoz-Sabater, 2019). The key 203 variables used include 2m temperature (T2M) for air temperature, surface solar radiation 204 downwards (SSRD) for shortwave radiation, and volumetric soil water of the second layer (7 to 205 28 cm depth; SM2) for soil moisture. This specific soil layer is chosen due to its higher 206 correlation with observed soil water content from flux tower stations, compared to other layers.

To assess drought episodes across south-western Europe, monthly averaged ERA5-Land variables, including T2M, SSRD and SM2, are employed. Monthly anomalies for these variables are calculated as the difference with monthly mean between 2001 and 2022. Additionally, the Standardized Precipitation Evaporation Index (SPEI) is computed at various months aggregations to assess drought intensity and variability using monthly averaged ERA5-Land
data. The SPEI aggregated over 1-, 3-, 6-, 9- and 12-months are named respectively SPEI01,
SPEI03, SPEI06, SPEI09 and SPEI12. SPEI is a multi-scalar drought index that considers not
only precipitation but also the hydrological balance with atmospheric evaporative demand
crucial for studying vegetation impacts in warm regions (Vicente-Serrano et al., 2010, 2013).
The computation of SPEI is explained in the Supporting information.

The EVI and the land surface water index (LSWI), are processed from the MODIS Terra satellite MOD09A1 v006 product (Vermote, 2015) using the VPRM preprocessor from the Department of Biogeochemical Systems in the Max Planck Institute for Biogeochemistry (https://www.bgc-jena.mpg.de/bgc-systems/pmwiki2/pmwiki.php/Download/VPRMpreproc).

The VPRM model uses the Synergetic Land Cover Product (SYNMAP) (Jung et al., 2006) for the vegetation classification map. SYNMAP is a 1-km global land cover product built from remote sensing observations and its classes are defined based on PFT mixtures with explicit leaf type and longevity definitions, ideal for carbon cycle modelling applications. The 48 land classes of the SYNMAP map were reclassified in the VPRM preprocessor to the 8 VPRM PFT.

To complement the analysis of VPRM simulations, we also estimate GEE based on the sun-induced chlorophyll fluorescence (SIF) provided by the Global Orbiting Carbon Observatory-2 (OCO-2) SIF product (GOSIF), following the methodology outlined by Li and Xiao (2019). GOSIF exhibits strong correlations with GEE at hourly, monthly, and annual scales, maintaining a high correlation with GEE even during drought episodes (Lv et al., 2023; Qiu et al., 2022), and offers the advantage of relying solely on satellite SIF observations, eliminating the need for climate data.

233 **2.4 Statistical analysis**

Monthly anomalies of GEE, R_{ECO} , and NEE are calculated at 9 km resolution, as the difference to monthly means (g C m⁻² month⁻¹) for the entire period 2001-2022. The methodology used to determine the long-term trend of the fluxes is detailed in Supporting information. This consists of a linear regression of the carbon fluxes anomalies time series and the significance of these trends is assessed using a Pearson correlation test.

To investigate the influence of SPEI at various timescales on the interannual variability 239 of fluxes, a Pearson correlation analysis is conducted using the time series of detrended flux 240 anomalies. In the case of the climate drivers (T2M, SM2 and SSRD), the partial correlation 241 coefficient is calculated for each variable controlling the interannual variations in the other two 242 driver variables. For this analysis, detrended anomalies are aggregated annually and for growing 243 season months, identified for each biogeographical region and average seasonal cycles. Growing 244 season months are determined based on when GOSIF GEE exceeds 30% of the intra-annual GEE 245 range. Although GOSIF GEE and VPRM GEE generally exhibit similar seasonal cycles across 246 all biogeographical regions, discrepancies are observed for the Iberian and Tyrrhenian-Adriatic 247 sclerophyllous regions (Figure S1). 248

Finally, we select three study cases consisting of years with severe heat and drought 249 events affecting largely the NEE of the south-western European ecosystems, to study intra-250 annual variations in biogenic carbon fluxes in response to these major events. The study cases 251 are the Western Europe region in the year 2003, the Iberian sclerophyllous region in the year 252 2005, and the Atlantic region in the year 2022. For these three study cases, VPRM-simulated 253 biogenic fluxes are aggregated on an 8-daily basis, along with T2M and SM2. Anomalies relative 254 255 to the means over the 2001-2022 period are computed for each grid cell and 8-daily period within the year. 256

257 **3 Results**

258 **3.1 Trends of south-western Europe biogenic carbon fluxes**

The long-term analysis of biogenic carbon fluxes from both VPRM and GOSIF shows an 259 overall increase of both GEE and R_{ECO}, with certain regions of flux stability (Figure 2). GOSIF 260 presents a positive trend in GEE (spatial median of 5.51 g C m⁻² year⁻² and 53.4% of the 261 vegetated areas in the domain have a significant increase in GEE), while VPRM positive GEE 262 trends are limited to the mountainous regions. Both models are consistent in estimating a non-263 significant negative trend in the GEE in the Massif Central mountains (south-central France) and 264 the south-west of the Iberian Peninsula. Both models agree that the Apennine and Corsican 265 biogeographical region presents the highest positive trends (spatial medians of 8.97 and 10.25 g 266

267 C m⁻² year⁻² for GOSIF and VPRM, respectively), and Western Europe the lowest trends (2.75 268 and 1.25 g C m⁻² year⁻²) (see Figure S2 in the Supporting information).

The long-term trends of the VPRM R_{ECO} present a similar spatial distribution to the trends of GEE, although the magnitude is smaller (spatial median of 3.06 g C m⁻² year⁻²) than for the GEE (3.75 g C m⁻² year⁻²). Based on the VPRM, the spatial extent of the areas with significant R_{ECO} trends (37.6%) extends further than the areas with significant GEE trends (27.2%), reflecting that the ecosystem respiration has a steadier increase than the gross ecosystem exchange.

This similar spatial distributions of the trends of the GEE and R_{ECO} reflect that long-term 275 variations in released and captured carbon by the ecosystems compensate each other, implying in 276 a trend approaching zero in the NEE (-0.80 g C m⁻² year⁻²) (Figure 2d). VPRM estimates a 277 significant annual increase of net carbon sink over specific regions located in the Alps (-2.35 g C 278 m⁻² year⁻²), and the Apennines, and Corsican (-3.83 g C m⁻² year⁻²) mountainous regions (Figure 279 S2). Only one region shows a decrease in net carbon sink (maximum trends of 11.69 g C m^{-2} 280 year⁻²) over the 2001-2022 period, located in the northern part of the Massif Central, although 281 not statistically significant. 282



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Figure 2. Long-term carbon flux trends. Spatial pattern of the long-term trends of annual fluxes for (a) GOSIF GEE; (b) VPRM GEE; (c) VPRM R_{ECO} ; (d) VPRM NEE between 2001 and 2022. The black dots correspond to areas where the linear regression is significant (p < 0.05).

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The seasonal analysis of the biogenic carbon flux trends show that spring is the season when GEE and R_{ECO} (NEE) exhibited higher (lower) values (Figure S3). During spring, the spatial medians of annual trends are of 0.66, 0.54, 0.31 and -0.24 g C m⁻² month⁻¹ year⁻¹ for the GOSIF GEE, VPRM GEE, R_{ECO} , and NEE, respectively. Larger discrepancies between GOSIF and VPRM GEE are present during summer, with 0.43 and 0.08 g C m⁻² month⁻¹ year⁻¹, respectively (Figure S3).

The disaggregation of the fluxes by plant functional types (PFT) reveals that the increase in the long-term trends of the GEE and R_{ECO} in the Po Basin, the Italian sclerophyllous, the Apennine and Corsican montane and the Tyrrhenian-Adratic sclerophyllous regions is mainly located over croplands (Figure 3). In other regions such as the Atlantic, the Iberian sclerophyllous and the Western European broadleaf regions, the long-term trends of the respiration are higher than for the GEE in croplands, counteracting the contributions of the natural PFT with stronger sink increases.



Figure 3. Long-term carbon flux trends by PFT. Average annual trends of the GEE and R_{ECO} aggregated annually for the different biogeographical regions and integrated for the different plant functional types. The PFT percent coverage in each biogeographical region is marked over each bar. EF: evergreen forest, DF: deciduous forest, MF: mixed forest, SHR: shrubland, SAV: savanna, CRO: cropland, GRA: grassland.

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Over the entire study area (Figure 4), both VPRM and GOSIF present a significant increase of the annual GEE of 6.5 and 9.4 Tg C year⁻², respectively. Both GOSIF and VPRM show a strong agreement on the interannual variability of the GEE. VPRM also presents a significant increase in R_{ECO} of 5.0 Tg C year⁻². This occurs in conjunction with a significant warming trend of 0.057 °C year⁻¹ and a non-significant soil drying trend of -0.0003 m³m⁻³ year⁻¹ over the region. Due to the compensation between GEE and R_{ECO} , the VPRM model shows a non-significant decrease in NEE in the study area of -1.5 Tg C year⁻². Moreover, the occurrence of summer heat and drought events increases the intra-annual variability of NEE, producing the largest positive NEE anomalies and contributing to destabilize the negative trend in the NEE.

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Figure 4. Time-series of annual anomalies over the study area. Annual anomalies in the climate 319 data and carbon fluxes during 2001-2022. (a) soil moisture and temperature, (b) GEE, (c) R_{ECO} 320 and (d) NEE aggregated annually over the entire study area (black box in Figure 1). The dashed 321 lines represent the trends, while in the boxes the trends and the p value are detailed. The black 322 stars in subplot (d) mark the years in which the SPEI aggregated over 1-, 3-, 6-, 9- or 12-months 323 324 during summer is below -1, indicating a drought affecting most of the study area. The red stars mark the years when the summer temperature anomalies are above 1 °C, indicating a summer 325 heat event. 326

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328 **3.2 Interannual variability of the biogenic carbon fluxes**

We show in Figure 5 the correlation between GEE and R_{ECO} interannual anomalies and 329 the SPEI aggregated over 1, 3, and 6 months (SPEI01, SPEI03 and SPEI06, respectively), and 330 331 the partial correlation with the climate drivers such as air temperature (T2M), soil moisture and radiation during the growing season months at the ten biogeographical regions. Water 332 availability prevails as the dominant driver of GEE interannual variability. Except for the Alps, 333 the strongest correlations with GEE anomalies are found for SPEI (spatial median ranges 334 335 between 0.38 and 0.76) and soil moisture (between 0.35 and 0.64). These results suggest that seasonal and extended droughts significantly influence GEE fluctuations. The correlations with 336 SPEI at higher timescale aggregations (9 and 12 months) show lower correlations (between 0.26 337 and 0.73) than for lower timescale (Figure S4). Excluding the Alps, soil moisture exhibits 338 generally significant positive partial correlations with GEE anomalies, while air temperature 339 (between -0.28 and 0.21) shows primarily non-significant negative partial correlations. Higher 340 temperatures during the growing season led to reduced CO₂ capture, while increased 341 precipitation and soil moisture promote the photosynthetic activity. Although radiation presents 342 a positive correlation with GEE, it is generally non-significant. Both GOSIF and VPRM show a 343 good agreement across biogeographical regions and climate drivers (Figure S4), confirming that 344 both models are able to simulate the observed interannual variability. 345

In semi-arid regions such as the Iberian sclerophyllous and Tyrrhenian-Adriatic regions, 346 with low annual precipitation ($< 800 \text{ mm year}^{-1}$) and early growing seasons (Figure S1), strong 347 positive correlations are found between SPEI aggregated over 6 months and GEE anomalies 348 (r=0.76 for IbeScl., and r=0.73 for TyrAdr.). During the growing season of low-altitude regions 349 (excluding Alps, Apennine, and Corsican montane forests), GEE exhibits generally negative 350 partial correlations with air temperature (between -0.28 and 0.01), while R_{ECO} shows positive 351 352 partial correlations (between 0.03 and 0.40). In temperate humid regions like the Atlantic, Western Europe and Po Basin, R_{ECO} displays weaker correlations with SPEI (r= 0.12 to 0.42) 353 compared to GEE (SPEI: r = 0.37 to 0.61), indicating that R_{FCO} is less sensitive to droughts in 354 such regions. Conversely, in south-eastern regions like Tyrrhenian-Adriatic, Apennine and 355

Corsican montane, R_{ECO} exhibits stronger correlations with SPEI and partial correlations with soil moisture (SPEI: r= 0.55 to 0.81; SM2: r= 0.61 to 0.79)

Annually-aggregated GEE anomalies show similar patterns with drought indices and 358 climate drivers (Figure S5), including SPEI and soil moisture, but weaker absolute values (SPEI: 359 0.14-0.60; SM2: 0.24-0.52), suggesting that climate driver strength throughout the year has a 360 smaller impact on annual anomalies compared to the growing season. However, excluding Alps, 361 Apennine and Corsican montane forests, annual aggregate GEE anomalies display higher 362 positive correlations with air temperature (between 0.00 and 0.28), indicating that off-season 363 temperature increases enhance gross carbon capture. In high-altitude regions, the partial 364 correlations of annual temperature and GEE anomalies are lower (between 0.09 and 0.40) than 365 during the growing season months (between 0.21 and 0.44). 366



Figure 5. Interannual drivers of carbon flux anomalies. Boxplots of correlation values between GEE and RECO detrended anomalies and the different climate drivers and drought indices aggregated over all the year for each biogeographical region. The median is represented with a yellow line. The discontinuous black lines represent the limit when correlations are significant (p<0.05). T2M: 2 m temperature. SM2: soil moisture between 7 and 28 cm depth. SSRD: surface solar radiation downwards.

We analyse the correlation between SPEI and GEE anomalies for the biogeographical 374 375 regions displaying significant trends (Figure 6, see Supporting information, Figure S6 for the 376 rest). This time-lagged analysis covers the summer season in the same year (0 months), spring in the same year (-3 months), and so forth, up to autumn two years before the growing season (-21 377 months). Generally, strong, and significant correlations exist between SPEI and GEE anomalies 378 379 during the growing season in the same year, gradually decreasing with earlier seasons. An 380 exception occurs in the Alps (Figure 6f), where SPEI displays a negative non-significant correlation in the same year's summer and spring, with the correlation increasing in the 381 preceding seasons until the previous autumn. In humid temperate regions like the Atlantic and 382 Western Europe, correlations decrease faster over time, becoming non-significant before the 383 summer season. We observe in these humid regions that correlations decrease much faster over 384 the previous seasons for R_{ECO} than for GEE (Figure S7). This is different from the Mediterranean 385 climate regions, such as Iberian and Tyrrhenian-Adriatic sclerophyllous, where significant 386 correlations persist even for the previous spring (-3 months) or winter (-6 months), both for GEE 387 and R_{ECO}. In these two regions, GEE anomalies exhibit a stronger correlation with short-time 388 scale droughts (SPEI01 and SPEI03) occurring during the spring than during the summer. 389



Figure 6. Correlogram between SPEI and GEE anomalies. Correlogram between the growing season anomaly in the GEE and the SPEI aggregated at 1 month (blue), 3 months (orange) and 6 months (green) averaged over the time-lagged previous seasons. 0 months represent the SPEI between June to August of the same year, -3 months the SPEI between March to May of the same year, and so on, until -21 months represent the SPEI between September to November of two years before the growing season. The bold lines represent the median correlation between all

the grid cells inside the biogeographical region, and the shaded areas represent the interquartilerange.

In the case of the NEE (Figure 7), we observe that for humid regions like the Atlantic and Western Europe, the correlation pattern is similar to the GEE but in opposite sign. However, in Mediterranean climate regions, such as Iberian and Tyrrhenian-Adriatic sclerophyllous, the correlations between NEE anomalies and droughts during summer, spring and winter are much lower in absolute value than for the GEE.





3.3 Intra-annual variability of the biogenic carbon fluxes

In the following section we study the intra-annual variability of the biogenic carbon 408 fluxes for three study cases. Figure 8a presents the temporal evolution of the biogenic flux 409 anomalies inside the Western Europe region in 2003. The model indicates reduced GEE from 410 June to September, reaching a minimum of -3.2 ± 1.7 g C m⁻²day⁻¹ (the error corresponds to 411 spatial standard deviation) in early August. R_{ECO} also shows a negative anomaly during summer, 412 albeit smaller than GEE, reaching only -1.3 ± 0.8 g C m⁻²day⁻¹. The region experienced low soil 413 moisture from March to September, exacerbated by high summer temperatures, especially during 414 a heat wave in August (+8 °C). This affected considerably the GEE and the NEE, presenting the 415 lowest values in the moment of maximum soil moisture anomaly, and turning the ecosystems in 416 the region from net carbon sinks into net carbon sources (Figure S8). The negative anomalies 417 during summer were partially offset by an increase in April, May, and June, linked to positive air 418 temperature anomalies (Figure 8d). The drought event of 2003 caused a 20.4 Tg C year⁻¹ (-38.8 419 %) reduction in net carbon capture in Western Europe region. The Atlantic, Po Basin, and Italian 420 sclerophyllous regions were also severely affected (Figure S9), with respective annual NEE 421 reductions of 11.5 Tg C year⁻¹ (-15.9 %), 7.8 Tg C year⁻¹ (-85.4 %) and 10.2 Tg C year⁻¹ (-40.8 422 %). Across the entire domain (Figure 1), the year 2003 had a net carbon loss of 99.6 Tg C year⁻¹ 423 (-34.1 %). 424

Figure 8b depicts the impact of the 2005 drought on biogenic carbon fluxes in the Iberian 425 sclerophyllous region. VPRM indicates reduced GEE and R_{ECO} from late January to October. 426 Higher GEE reductions appear in late April and May (-1.9 \pm 1.0 g C m⁻²day⁻¹). GEE and R_{ECO} 427 anomalies evolve similarly, although the impact on the R_{ECO} is lower (-1.6 \pm 0.7 g C m⁻²day⁻¹). 428 Climate driver anomalies (Figure 8e) reveal persistent negative soil moisture anomalies, dipping 429 to -0.08 m³m⁻³ from the start of the year to October, particularly during spring when fluxes are 430 lowest. Negative temperature anomalies (below -5 °C) were observed during winter, delaying 431 the beginning of the growing season, while May-July featured positive temperature anomalies (> 432 3 °C), further depleting soil moisture. The event led to a 64.9 Tg C year⁻¹ (-25.0 %) reduction in 433 annual GEE, and 47.1 Tg C year⁻¹ (-18.6 %) decrease in annual R_{ECO}, resulting in a 17.8 Tg C 434 year⁻¹ (-281.4 %) NEE decrease. The Atlantic, Iberian montane, north-eastern Spain and southern 435 France regions also experienced NEE reductions (Figure S10) of 11.0 Tg C year⁻¹ (-15.2 %), 6.5 436 Tg C year⁻¹ (-35.4 %) and 3.2 Tg C year⁻¹ (-17.9 %), respectively. In the south-western European 437 region, the 2005 drought caused a total reduction of 66.5 Tg C year⁻¹ (-22.8 %). 438

In 2022, south-western Europe experienced its hottest recorded summer, coupled with an 439 extended drought event extending from winter until November (Copernicus Climate Change 440 Service (C3S), 2023). Winter and spring precipitation and soil moisture deficits further increased 441 during summer due to the unusual warmer temperatures and multiple heat wave episodes 442 (Copernicus Climate Change Service (C3S), 2023). Figure 8c shows the 2022 spatial mean GEE 443 and R_{ECO} anomalies in the Atlantic region. GEE remains persistently low from June to August, 444 except for early July. R_{ECO} also showed negative summer anomalies, although for a shorter 445 period and with smaller reductions than GEE. During spring, GEE and R_{ECO} experienced 446 positive anomalies (over 2.1 ± 0.9 g C m⁻²day⁻¹), driven by the exceptionally high temperatures 447 during May (over +4 °C) (Figure 8f). The VPRM model estimates an annual decrease of the net 448 carbon capture of 13.8 Tg C year⁻¹ (-19.1 %) in the region and 78.5 Tg C year⁻¹ (-26.9 %) in the 449 south-western European domain. 450



Figure 8. Intra-annual impact of heat and droughts. Time series of the spatially average anomalies for the Western European in 2003 (a,d), Iberian sclerophyllous in 2005 (b,e), and Atlantic mixed forest in 2022 (c,f) for (a,b,c) 8-daily GEE (blue), R_{ECO} (orange) and NEE (pink). (d,e,f) spatially averaged 8-daily 2 m temperature (red) and soil moisture in the 7-28 cm depth layer (green) for the study year (dotted line) and the climatic mean for the 2001 to 2022 period (solid line). The shaded areas correspond to the temporal standard deviation for each 8-daily period.

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461 4 Discussion

462 **4.1 Long-term trends of the biogenic carbon fluxes**

In this study, we analysed the long-term trends and interannual variability of biogenic 463 carbon fluxes in the south-western European region from 2001 to 2022, to understand the 464 response of these fluxes to heat and drought events. The statistical analysis of the biogenic 465 carbon fluxes reveals an overall increase or stability of GEE (spatial median of 5.51 g C m⁻² year 466 ² for GOSIF and 3.75 g C m⁻² year⁻² for VPRM) and R_{FCO} (3.06 g C m⁻² year⁻² for VPRM). These 467 trends are particularly prominent in spring and in montane regions like the Alps, Apennines, 468 Pyrenees, and Dinaric Alps. We identify a positive trend of the enhanced vegetation index (EVI) 469 derived from MODIS surface reflectances (Vermote, 2015) over the Mediterranean region 470 (trends up to 0.0014 EVI year⁻¹) which is more evident during the spring and winter months 471 (Figure S11). Additionally, when examining long-term trends in the air temperatures using 472 ERA5-Land data (Muñoz-Sabater, 2019) (Figure S12), a more substantial winter warming (up to 473 $0.2 \,^{\circ}\text{C} \,\text{vear}^{-1}$) is observed over these same regions. The temperature rise during the colder season 474 475 contributes to the increase in GEE and R_{ECO} values by alleviating growth limitations and extending the growing season (Keenan et al., 2016). This is supported by similar increases in the 476 GOSIF dataset, which relies solely on SIF satellite data (Li & Xiao, 2019), reinforcing the notion 477 of elevated carbon capture in high-altitude regions of the south-western European region. 478

However, differences between GOSIF and VPRM are observed in other biogeographical 479 regions, possibly due to differences in model parameterization and input data. The discrepancies 480 between the two models impairs our ability to conclude about the long-term trends in NEE. 481 GOSIF exhibits overall a higher spatial median compared to VPRM. GOSIF solely relies on SIF 482 data and an ensemble of SIF-GEE linear relationships computed from global flux tower data, 483 484 whereas VPRM combines remotely sensed vegetation indices, meteorological data, and region-485 specific model parameters. Consequently, the long-term increase in GOSIF is directly linked to SIF data, whereas VPRM's response is influenced by both vegetation indices and climate 486 drivers. The higher sensitivity of VPRM to interannual climate variations explains the lower 487

extension of areas with a significant long-term trend. Additionally, VPRM is more responsive to
higher temperatures during the growing season (Figure S12), particularly in summer and autumn,
and the decrease in the soil moisture (Figure S13), over the south-western Iberian Peninsula and
the Central Massif of France.

According to VPRM simulations, long-term trends indicate that R_{ECO} has also increased 492 in the past two decades, at a slower rate than GEE but affecting a larger area (see Figure 2). The 493 increase in R_{ECO}, especially in high-altitude regions, partially offsets the increase in GEE, 494 resulting in only a modest increase in the NEE carbon sink (0.80 g C m⁻² year⁻²). This balance 495 suggests that the south-western Europe ecosystems maintain equilibrium between increased 496 carbon uptake through photosynthesis and carbon released through respiration. Unlike temperate 497 and boreal forests, which are experiencing a long-term increase of their carbon sink potential 498 499 (Yang et al., 2023; Yu et al., 2022), the Mediterranean regions exhibits balanced long-term carbon cycle trends. Ongoing warming and drying trends in the region may lead to 500 uncompensated responses in GEE and R_{ECO}, causing variations in the NEE trends. For instance, 501 we have identified a positive trend in NEE of croplands in the Central Massif of France (Figure 502 503 3e) coinciding spatially with a drying trend in the region (Figure S13) (X. Liu et al., 2021). These prospects could further compromise the net carbon sink capacity of other agricultural 504 505 ecosystems in south-western Europe as the ongoing drying trend (Figure 4a) continues and affects other regions in the domain. These findings highlight the vulnerability of the south-506 507 western European region's carbon sink capacity to potential shifts in carbon flux trends, especially under the influence of more frequent and intense droughts. 508

509 **4.2 Heat and drought events control the interannual variability of the fluxes**

The analysis of the interannual variability in biogenic carbon fluxes emphasizes the 510 significant influence of climatic drivers on the detrended anomalies of these fluxes. Across all 511 the biogeographical regions, except for the Alps ecosystems, water availability emerges as the 512 513 dominant climatic driver for interannual variabilities (see Figure 5). This is evident through the strong correlation observed between these fluxes and both soil moisture and the SPEI. The close 514 agreement between VPRM and GOSIF correlations further supports the influence of soil 515 moisture and SPEI on GEE variability. This alignment is notable, considering that initially, one 516 517 might attribute this relationship to soil moisture as a driver of the VPRM model.

Analysing the influence of climate drivers on GEE reveals a direct link between climate 518 dryness and the extent to which droughts influence the interannual variabilities of GEE. The 519 regions where the water balance plays a more important role on the interannual anomalies of the 520 GEE during the growing season are the semi-arid regions of the Iberian and Tyrrhenian-Adriatic 521 sclerophyllous and mixed forests (see Figure 5). In these regions, GEE is strongly correlated with 522 the occurrence of droughts during the growing season and in the previous six months (from the 523 previous autumn forward). These findings align with previous research by Gouveia et al. (2017), 524 who noted that, during the month of May, Mediterranean dry vegetation communities present the 525 highest correlations between the vegetation activity and the SPEI aggregated at time scales 526 between 3 and 9 months, which are associated with croplands. These regions have a high 527 extension of non-forest vegetation (more than 85 % of the vegetated areas) and the lowest annual 528 precipitation among the studied biogeographical regions (less than 800 mm), explaining the 529 heightened sensitivity to soil moisture availability during periods of active vegetation growth 530 (Vicente-Serrano, 2007). In contrast, the Alps, characterized by the lowest annual temperatures 531 $(3.8^{\circ}C)$ and the highest precipitation levels (1485 mm) in the study area, exhibit a positive 532 533 correlation with air temperature and negative correlations with SPEI and soil moisture. This pattern suggests that the Alps' vegetation faces continuous energy limitations. Warmer 534 535 temperatures and increased solar radiation tend to bring climatic conditions closer to the optimal temperatures for photosynthesis (between 18 and 22 °C), while regional droughts have a 536 537 relatively lower impact on the water availability of the region.

While increased air temperatures negatively impact GEE anomalies (except for the Alps), 538 their impact on the R_{FCO} is less pronounced. These differences can be attributed to distinct 539 ecophysiological responses of photosynthesis and respiration to temperature and soil moisture 540 stress. Air temperature impacts the photosynthesis when it surpasses a certain optimum 541 temperature by reducing the chemical reaction kinetics (von Buttlar et al., 2018), whereas soil 542 moisture stress impacts photosynthesis by ecophysiological and structural changes (Bréda et al., 543 2006). On the other hand, increasing soil temperatures, and hence air temperatures, stimulates 544 heterotrophic respiration by increasing the kinetics of soil microbial decomposition, root 545 respiration and the diffusion of enzymes (von Buttlar et al., 2018), while strong soil moisture 546 deficits produced by droughts affects negatively the soil microbial activity and reduces 547 autotrophic respiration due to the reduction of recently assimilated carbon (Migliavacca et al., 548

549 2011; Reichstein et al., 2003). Therefore, while an increase of temperature during the growing 550 season can be negative for the photosynthesis, especially if it is accompanied by a drought, the 551 impact on the ecosystem respiration is reduced by the compensating effects. It is worth noting 552 that these responses vary depending on the ecosystem and vegetation species.

Our analysis reveals a higher influence of droughts on GEE anomalies compared to R_{ECO} 553 anomalies in temperate humid regions like the Atlantic, Western Europe, and the Po Basin 554 regions. In contrast, the impacts of droughts on GEE and R_{ECO} in other Mediterranean climate 555 regions show similar correlations. The different responses of GEE and R_{ECO} to drought 556 occurrences between humid and dry climates may be attributed to various factors, including 557 higher intra-annual compensation effect for R_{ECO} compared to GEE in humid regions, the 558 resistance capacity of Mediterranean vegetation to seasonal droughts (Gazol et al., 2018), and 559 lagged responses of R_{ECO} to drought compared to more immediate effects on GEE (Ryan & 560 Law, 2005). These findings align with previous studies on the 2003 summer drought and heat 561 event in Central Europe (Ciais et al., 2005; Reichstein et al., 2007), which reported a higher 562 impact of drought on GEE compared to R_{ECO} in temperate ecosystems. We note that temperate 563 humid regions exhibit the highest net carbon sink in the study area (see Figure S14) but also 564 higher nonlinearities in the response of GEE and R_{ECO} to drought occurrence during the growing 565 season. Consequently, anomalies in NEE are highly influenced by droughts in these regions 566 compared to Mediterranean regions (Figure S15). These results emphasize the vulnerability of 567 the south-western Europe's net carbon sink to drought occurrences. 568

569 4.3 Warm springs do not compensate the decreasing effect of droughts on CO₂ fluxes

We find that both GEE and R_{ECO} decrease during the summer for Western European broadleaf forests in 2003 and the Atlantic mixed forests in 2022, revealing similar impact of heat and water stress on the ecosystem carbon fluxes. This can be explained by the heat wave in conjunction with persistent drought conditions (Bastos et al., 2014; García-Herrera et al., 2010) as shown by several studies on the coupled effects of heat and water stress on the photosynthetic capacity of Mediterranean ecosystems (Bastos et al., 2014; Ciais et al., 2005; Ermitão et al., 2021; Reichstein et al., 2007).

However, the impact of heat-drought combined conditions on R_{ECO} is lower than for 577 GEE. Moreover, the impact on the R_{ECO} seems to be lagged with respect to the GEE, starting to 578 stress between 8 and 16 days after the stress is observed in the GEE, while recovering 579 concurrently to the GEE once the heat and water stress subsided. These differential responses 580 between GEE and R_{ECO} resulted in a reduction of the net carbon capture capacity of the 581 ecosystems and turning ecosystems from net carbon sinks to carbon sources (see Figure S8). 582 These results align with the ones obtained by (von Buttlar et al., 2018), who found from eddy-583 covariance flux measurements that the combination of drought and heat typically led to a strong 584 decrease in GEE, whereas heat and drought impacts on respiration partially offset each other. 585

For the 2003 and 2022 study cases, we find that the impact of summer heat and drought 586 events are partially compensated by abnormally warm temperatures between April and June, 587 which led to an increase in GEE and R_{ECO}. The impact of the warm spring temperatures 588 produced similar positive anomalies in magnitude on the GEE and R_{ECO}. The high spring R_{ECO} 589 anomaly detected in these two study cases could be attributed to the combination of high spring 590 591 temperatures and the high GEE anomalies at the peak of the growing season, causing an increment of the recently assimilated carbon to respire. The similar increment of the GEE and 592 R_{ECO} during spring compensates each other, resulting in a minimal NEE anomaly during the 593 spring. 594

These distinct seasonal compensation effects between spring and summer led to an overall reduction in NEE compared to normal values during the growing season, dominating the anomalies for the entire year. These findings highlight the importance of studying the combined impacts of heat and drought events on both GEE and R_{ECO} , as they can cause non-linear effects on the terrestrial carbon balance. Focusing solely on GEE might underestimate the true impact of heat and drought events on ecosystems, and the terrestrial carbon balance.

These results suggests that the Mediterranean ecosystems, adapted to recurrent seasonal droughts during the summer (Peñuelas & Sardans, 2021), are more vulnerable to the occurrence of persistent soil moisture deficits at the beginning of the growing season, especially if persistent drought conditions affect the previous humid seasons. The Iberian sclerophyllous region is principally cultivated with winter crops (Gouveia et al., 2017), which can be affected by water deficits at early stages of crop development. Moreover, the cold winter conditions during 2005 in the Iberian Peninsula (anomalies of -5° C) may have also affected GEE by delaying the beginning of the growing season or with a direct frost damage. These results highlight the potential recurrent stress that will suffer the Iberian ecosystems under future climate scenarios, and the compromised carbon balance from these ecosystems (Moemken et al., 2022).

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612 **4.4 VPRM modifications improve the response of the fluxes to heat and drought**

We modified the data-driven biosphere model VPRM for GEE and R_{ECO} 613 parameterizations, incorporating plant functional type-specific parameters calibrated using data 614 solely from flux tower stations in the southern Europe and neighbouring regions. These 615 modifications include the inclusion of soil moisture-related water stress in the GEE 616 parameterization (Fu et al., 2022), resulting in improved model GEE estimates that better align 617 with changes between energy and water-limited regimes. This modification improves the 618 correlation between modelled-predicted and observed weekly GEE estimates in evergreen-leaf 619 ecosystems, such as Mediterranean evergreen forests (cf. Supporting information). Additionally, 620 we implemented a more sophisticated semi-empirical R_{FCO} parameterization that considers 621 vegetation productivity (GEE) and soil moisture, enhancing the predictive capability of the 622 model to analyse seasonal and annual variations of the carbon balance (Migliavacca et al., 2011). 623

However, several limitations emerge from the VPRM model for long-term biogenic flux 624 studies. For instance, the VPRM model relies on a land cover map based on the Synergetic Land 625 626 Cover Product (SYNMAP) (Jung et al., 2006), which joins three global land cover products based on satellite observations as recent as 2001, failing to account land-use/land-cover changes 627 628 during the 2001 to 2022 period. This limitation could be solved by incorporating dynamic landcover maps as the MODIS MCD12Q1 product (Friedl & Sulla-Menashe, 2019). Moreover, the 629 application of static parameters for each PFT for the 2001 to 2022 period could not properly 630 capture the increase in the light-use-efficiency factor due to the atmospheric CO₂ fertilization 631 632 effect (Keenan et al., 2016). A dynamic set of VPRM parameters, updated every few years, could 633 address this issue, provided a continuous and standardized dataset of carbon flux tower observations encompassing various biogeographical regions, climates and PFT becomes 634 available. Despite the commendable efforts of organizations like FLUXNET (Pastorello et al., 635 2020) and the Integrated Carbon Observation System (ICOS), certain biomes and PFT remain 636 underrepresented in observation datasets, as it is the case of the croplands in semi-arid regions of 637

the Iberian, Tyrrhenian, and Adriatic sclerophyllous regions. This underrepresentation contributes to model uncertainties in estimating biogenic fluxes in these regions. The VPRM predicting capabilities and the analysis of the carbon balance would benefit from the incorporation of novel flux tower sites in these underrepresented biomes and PFT.

Despite the enhancements made to the R_{ECO} parameterization, the model evaluation 642 reveals moderate correlations with R_{ECO} observations, compared to GEE and NEE (Figure S18, 643 in Supporting information). This discrepancy suggests the existence of unaccounted processes 644 645 within the model. These processes could relate to carbon pool size (Reichstein et al., 2003), the maximum leaf area index throughout the year, nitrogen deposition, and stand age (Migliavacca et 646 al., 2011) in natural ecosystems. In the case of croplands, factors like management practices and 647 soil carbon pools could potentially influence respiration (Eugster et al., 2010). Addressing these 648 649 aspects could improve R_{ECO} estimation but may introduce additional sources of model uncertainty due to increased complexity. Overcoming these sources of uncertainty may be 650 651 possible through regional-scale inverse analysis of the CO_2 budget (Mahadevan et al., 2008), leveraging atmospheric CO₂ concentration observations from towers in south-western Europe 652 653 (Kountouris et al., 2018; Munassar et al., 2022).

654 **5 Conclusions**

Using a modified VPRM model with parameters optimized for south-western Europe 655 ecosystems, this study analysed the long-term trends and interannual variability of carbon fluxes 656 657 in south-western Europe from 2001 to 2022, to understand the response of these fluxes to heat and drought events. Our results revealed high spatial variations of the carbon fluxes trends, being 658 higher over mountainous regions in the Alps, Apennine, and Corsican montane forests. The 659 similar increases of the ecosystem's photosynthesis and respiration compensate each other, 660 resulting in only a modest increase of 0.80 g C m⁻² year⁻² (spatial median) in net carbon capture 661 over the region. Ongoing warming and drying trends in the region may lead to uncorrelated 662 responses in gross ecosystem exchange and ecosystem respiration, causing variations in the net 663 ecosystem exchange trends. These findings highlight the vulnerability of the south-western 664 Europe's carbon sink capacity to potential shifts in carbon flux trends, especially under the 665 influence of more frequent and intense droughts. 666

667 Analysing the influence of climate drivers on the gross ecosystem exchange and 668 respiration reveals a direct link between climate dryness and the extent to which droughts

influence the interannual variabilities of the carbon fluxes. The regions where the water balance 669 plays a more important role on the interannual anomalies of the gross ecosystem exchange and 670 respiration during the growing season are the semi-arid regions of the Iberian and Tyrrhenian-671 Adriatic sclerophyllous regions. These regions, contrary to the other regions, present a higher 672 influence of droughts on the gross ecosystem exchange variability during the spring, rather than 673 on summer. However, this analysis reveals a higher influence of droughts on gross ecosystem 674 exchange anomalies compared to ecosystem respiration anomalies in temperate humid regions 675 like the Atlantic, Western Europe, and the Po Basin. We show here that temperate humid regions 676 exhibit the highest net carbon sink in our study area but also display highly nonlinear responses 677 of the carbon fluxes to drought occurrence during the growing season. Consequently, anomalies 678 in net ecosystem exchange are highly influenced by droughts in these regions compared to 679 680 Mediterranean regions. These results emphasize the vulnerability of the south-western Europe's net carbon sink capacity to drought occurrences. Additionally, we observed that the impact of 681 summer heat and drought events reduces the net carbon capture, even turning ecosystems from 682 carbon sinks to carbon sources, while we did not observe intra-annual compensations from the 683 684 preceding warm spring due to compensating increases in gross ecosystem exchange and respiration. These findings emphasize the importance of studying the combined impacts of heat 685 and drought events on both ecosystem photosynthesis and respiration, as they can cause non-686 linear impacts on the terrestrial carbon balance. 687

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709 **Open Research**

The VPRM version with the modifications detailed in this study are available in a Python 710 program in the repository "Vegetation Photosynthesis and Respiration Model code and output for 711 712 south-western Europe between 2001 and 2022" at Zenodo, via https://doi.org/10.5281/zenodo.10782550 with Creative Commons Attribution 4.0 International 713 license (Villalba, 2024). In this repository there are also the terrestrial ecosystem carbon fluxes 714 715 estimated with the modified VPRM over the south-western Europe domain between 2001 and 2022 used in this study in NetCDF format. The hourly ERA5-Land data (Muñoz-Sabater, 2019) 716 was downloaded from the Copernicus Climate Change Service (C3S) Climate Data Store (2022). 717 718 Neither the European Commission nor ECMWF is responsible for any use that may be made of manuscript submitted to Global Biogeochemical Cycles

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