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Regional-scale analysis of carbon and water cycles on managed grassland systems

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► **To cite this version:**

Shaoxiu Ma, Romain Lardy, Anne-Isabelle Graux, Haythem Ben Touhami, Katja Klumpp, et al.. Regional-scale analysis of carbon and water cycles on managed grassland systems. *Environmental Modelling and Software*, 2015, 72, 10.1016/j.envsoft.2015.03.007 . hal-01210951

HAL Id: hal-01210951

<https://hal.science/hal-01210951v1>

Submitted on 28 May 2020

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5 **1 Regional-scale analysis of carbon and water cycles on**
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7 **2 managed grassland systems**
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13 6 Shaoxiu Ma¹, Romain Lardy^{2,3}, Anne-Isabelle Graux⁴, Haythem Ben Touhami¹, Katja
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5 **15 Abstract:**
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7 16 Predicting regional and global carbon (C) and water dynamics on grasslands has
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9 17 become of major interest, as grasslands are one of the most widespread vegetation
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11 18 types worldwide, providing a number of ecosystem services (such as forage
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13 19 production and C storage). The present study is a contribution to a regional-scale
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15 20 analysis of the C and water cycles on managed grasslands. The mechanistic
16
17 21 biogeochemical model PaSim (Pasture Simulation model) was evaluated at 12
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19 22 grassland sites in Europe. A new parameterization was obtained on a common set of
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21 23 eco-physiological parameters, which represented an improvement of previous
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23 24 parameterization schemes (essentially obtained via calibration at specific sites). We
24
25 25 found that C and water fluxes estimated with the parameter set are in good agreement
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27 26 with observations. The model with the new parameters estimated that European
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29 27 grassland are a sink of C with $213 \text{ g C m}^{-2} \text{ yr}^{-1}$, which is close to the observed net
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31 28 ecosystem exchange (NEE) flux of the studied sites ($185 \text{ g C m}^{-2} \text{ yr}^{-1}$ on average).
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33 29 The estimated yearly average gross primary productivity (GPP) and ecosystem
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35 30 respiration (RECO) for all of the study sites are 1220 and $1006 \text{ g C m}^{-2} \text{ yr}^{-1}$,
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37 31 respectively, in agreement with observed average GPP ($1230 \text{ g C m}^{-2} \text{ yr}^{-1}$) and RECO
38
39 32 ($1046 \text{ g C m}^{-2} \text{ yr}^{-1}$). For both variables aggregated on a weekly basis, the root mean
40
41 33 square error (RMSE) was $\sim 5\text{-}16 \text{ g C week}^{-1}$ across the study sites, while the goodness
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43 34 of fit (R^2) was $\sim 0.4\text{-}0.9$. For evapotranspiration (ET), the average value of simulated
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45 35 ET (415 mm yr^{-1}) for all sites and years is close to the average value of the observed
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47 36 ET (451 mm yr^{-1}) by flux towers (on a weekly basis, $\text{RMSE} \sim 2\text{-}8 \text{ mm week}^{-1}$;
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5 37 $R^2=0.3-0.9$). However, further model development is needed to better represent soil
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7 38 water dynamics under dry conditions and soil temperature in winter. A quantification
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9 39 of the uncertainties introduced by spatially generalized parameter values in C and
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11 40 water exchange estimates is also necessary. In addition, some uncertainties in the
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13 41 input management data call for the need to improve the quality of the observational
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15 42 system.
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28 **Key word:**

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31 47 Carbon flux, eddy flux measurements, model evaluation, Pasture Simulation model
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33 48 (PaSim), water balance
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50 **Software availability**

51 Name of Software: Pasture Simulation model (PaSim)
52 Developer: INRA, UR0874 initiative; contact: Raphaël Martin
53 Contact Address: INRA, UR0874 Grassland Ecosystem Research, 63039
54 Clermont-Ferrand, France
55 Telephone: +33-4-73624872
56 E-mail: raphael.martin@clermont.inra.fr
57 Availability: On request to the authors
58 Cost: free for no-profit use
59 Program language: Fortran

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1. Introduction

Accurate quantification of ecosystem carbon (C) and water fluxes over regions, continents, or the globe is essential for understanding the feedbacks between the terrestrial biosphere and the atmosphere in the context of global change and climate policy-making (Xiao et al., 2012; Ciais et al., 2013). In the last decades, significant progresses have been made in quantifying regional to global C and water fluxes by using ecosystem modelling (Jung et al., 2007; Xiao et al., 2009), atmospheric inverse modelling (Butler et al., 2010) and upscaling of flux observations from eddy covariance towers (Jung et al., 2011). In particular, integrated environmental modelling (Laniak et al., 2013) provides effective tools for studying C and water cycles in agricultural and natural systems. Ecosystem models have been intensively developed and used to estimate C and water exchanges between the atmosphere and biosphere (Bondeau et al., 1999; Churkina et al., 1999; Huntzinger et al., 2012; Warszawski et al., 2014). They represent the key processes (such as plant photosynthesis, ecosystem respiration and evapotranspiration) and climatic and management drivers (e.g. grazing, cutting and fertilization) that regulate energy and matter exchanges. However, most of the modelling efforts have focussed on forests (Bondeau et al., 1999; Schaefer et al., 2012; Wu et al., 2012) and croplands (Palosuo et al., 2011; Roetter et al., 2012; Wattenbach et al., 2010), while lesser attention was given to grasslands (Ciais et al., 2010).

Grasslands are a widespread vegetation type worldwide, covering nearly one-fifth of the world's land surface (24 million km²) (Suttie et al., 2005) and playing a significant

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5 84 role in the global C cycle (Scurlock and Hall, 1998; Ciais et al., 2010). At global scale,
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8 85 grasslands were estimated to be a net C sink of about 0.5 Pg C per year (Scurlock and
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10 86 Hall, 1998), but with high spatial heterogeneity and considerable uncertainty on the
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12 87 estimate of C exchange. Janssens et al. (2005) estimated that grasslands provide a C
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14 88 sink of 66 ± 90 g C m⁻² yr⁻¹ over Europe. From an extensive network of flux towers,
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16 89 Schulze et al. (2009) inferred a net C sink: net biome production (NBP) in European
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18 90 grasslands of 57 ± 34 g C m⁻² yr⁻¹. However, grassland ecosystems are the most
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20 91 uncertain components of the Europe-wide C balance in comparison to forests and
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22 92 croplands because only few data and grassland-specific models are available (Ciais et
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24 93 al., 2010). As a consequence, it is urgent to improve and evaluate grassland models
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26 94 based on recently-available eddy flux data.
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34 95 Over the last decades, grassland models were developed with different research foci.
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36 96 CENTURY model was developed to simulate soil C, N, P, and S dynamics on a
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38 97 monthly time step (Parton, 1988), with an updated version (DayCent) working on a
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40 98 daily basis (Parton et al., 2007). The Grassland Ecosystem Model (GEM) (Chen et al.,
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42 99 1996) linked biochemical, biophysical and ecosystem processes in a hierarchical
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44 100 approach to simulate C and N cycles, with focus on natural grasslands. The LINGRA
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46 101 model (Schapendonk et al., 1998) has been extensively applied to simulate growth of
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48 102 grasses, including perennial ryegrass (Rodriguez et al., 1999) and timothy (van Oijen
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50 103 et al., 2005) under northern and western European conditions. The Hurley Pasture
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52 104 Model (Thornley, 1998) describes the fluxes of C, N and water in a grazed
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54 105 soil-pasture-atmosphere system. DairyMod was designed to simulate not only
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5 106 biophysical, but also dairy management options (Johnson et al., 2008). Several
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7 107 integrated or whole farm system models were also available to simulate the
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9 108 biogeochemical processes and also include decision support system, such as Whole
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11 109 Farm Model (Bright et al., 2000), GP-FARM (Ascough et al., 2007), Integrated Farm
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13 110 System Model (<http://www.ars.usda.gov/Main/docs.htm?docid=8519>) and FASSET
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15 111 (Chirinda et al., 2011). An overview of the state of the art and the developments
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17 112 needed for process-based modelling of grazed agricultural systems were addressed by
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19 113 Snow et al. (2014).
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21 114 Recently, attempts have also been made to introduce management options into global
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23 115 dynamic vegetation and crop models in order to extend functionalities for grasslands
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25 116 on regional and global scales. Biome and global dynamic vegetation models such as
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27 117 LPJmL (Bondeau et al., 2007), Biome-BGC (Hidy et al., 2012), ORCHIDEE (Krinner
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29 118 et al., 2005) and CARAIB (Warnant et al., 1994) were improved with mowing and
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31 119 grazing options. At the same time, widely used crop models, such as STICS (Brisson
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33 120 et al., 2003; Ruget et al., 2009), EPIC (Williams et al., 1989), CropSyst (Stöckle et al.,
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35 121 2003), DNDC (Rafique et al., 2011; Wang et al., 2012), DSSAT (Giraldo et al., 1999)
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37 122 and the APSIM platform (Holzworth et al., 2014) have also been adapted to simulate
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39 123 grasslands. These efforts have made great contributions to the overall development of
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41 124 grassland models (yet with a different detail in representing processes). However,
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43 125 model evaluation was limited in scope to specific goals (e.g. not all grassland models
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45 126 simulate biogeochemical cycles). A detailed evaluation of model performance against
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47 127 observational flux data from a variety of grassland sites is therefore desirable. In
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5 128 particular, for a process-based model representing in detail the mechanisms driving
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7 129 the functioning of grassland systems, evaluation is needed with extended datasets,
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10 130 which include different grassland observational sites with a diversity of climatic,
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12 131 management and soil conditions.

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15 132 The process-based biogeochemical Pasture Simulation model (PaSim) is the focus of
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17 133 this study. It was originally developed by Riedo et al. (1998), based on the Hurley
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19 134 Pasture Model (Thornley, 1998), to simulate managed grasslands (clover-ryegrass
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21 135 swards). PaSim includes both grazing and cutting management options and is able to
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23 136 simulate a variety of temperate grassland ecosystems. Over the last decade, the model
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25 137 has been continuously improved to simulate C, water and N cycles. New approaches
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27 138 were integrated into the modelling structure to simulate, for instance, nitrous oxide
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29 139 (N_2O) emissions from soils (Schmid et al., 2001a) and methane (CH_4) emissions from
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31 140 animals (Vuichard et al., 2007a) as well as the performances (i.e. milk and meat
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33 141 production) of grazing animals (Graux et al., 2011). The model has been used in the
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35 142 climate-change impact studies (Graux et al., 2013; Vital et al., 2013), including an
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37 143 assessment of the contribution of forage-based systems to the global warming (Graux
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39 144 et al., 2012) with focus on France. However, PaSim has only been evaluated against a
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41 145 few European grassland sites using short periods of observed C fluxes and biomass
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43 146 production data, and based on limited parameterization (Vuichard et al., 2007a;
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45 147 Calanca et al., 2007). A full documentation and an extended evaluation of the model
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47 148 over a large number of sites are required.

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59 149 A monitoring network consisting of a total of 12 grassland sites was established in
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5 150 2002 and eddy-covariance flux measurements were made on this network within the
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8 151 European projects of the 5th, 6th and 7th framework programs, such as GREENGRASS
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10 152 (Soussana et al., 2007b), CARBOMONT (Bahn et al., 2008; Wohlfahrt et al., 2008),
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12 153 CarboEurope (Gilmanov et al., 2010) and CARBO-Extreme (Reichstein et al., 2013).
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15 154 This dataset provides a good opportunity to evaluate grassland model performances
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17 155 because these sites cover a variety of grassland types with contrasting management
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19 156 practices and representing different climate conditions.
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22 157 The present study assesses the ability of PaSim to reproduce C and water fluxes of a
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24 158 number of European long-term eddy flux measurement sites. To do so, three sets of
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26 159 eco-physiological vegetation parameters (i.e. from permanent grassland, sown
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28 160 grassland, and an adjusted set, which is the calibrated parameter values based on flux
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30 161 measurements data and their plausible ranges) were applied in order to test whether a
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32 162 common set of vegetation parameters is appropriate to represent model outputs at
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34 163 European scale (regardless of the possible physiological dissimilarities among
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36 164 grasslands species in different places in Europe). Model calibration was not applied
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38 165 separately to each observational site. This did not make it possible to explore the
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40 166 spatial variability of model parameters. Testing such a scenario appeared beyond the
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42 167 scope of this paper since it implied too strong a deviation from the initial hypothesis
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44 168 of this regional study. Rather, we calibrated the model simultaneously on all datasets
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46 169 to find parameter values that would be applicable at regional scale. Multi-site
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48 170 calibration can be characterized by lower uncertainty than site-specific calibration,
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50 171 because more data are involved in the calibration process (e.g. Minunno et al., 2014).

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5 172 The availability of a variety of detailed flux data from multiple sites offers the
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8 173 possibility of a genuine multi-location calibration of the model, holding to the
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10 174 assumption that a uniform calibration across sites is appropriate under these
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12 175 conditions. The results are discussed with respect to the strengths and weaknesses of
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15 176 the model in estimating C and water balances in Europe before presenting conclusions
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18 177 and avenues for future research.
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179 **2. Materials and Methods**

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181 **2.1 Study sites and climate data**

182 Twelve grassland sites with long-term eddy flux measurements were included in the
183 study to evaluate model performances. The study sites cover a broad gradient of
184 geographic and climatic conditions (Table 1) as well as a variety of soil types and
185 management practices (Table 2). The sites are located in Central and Western Europe
186 (Fig. 1, left), distributed over a range of latitudes from United Kingdom (Easter Bush)
187 to Portugal (Mitra), of longitudes from Ireland (Dripsey) to Hungary (Bugac-Puszta),
188 and of elevations from sea level up to mountain sites located at about 1800 m a.s.l.
189 (Table 1). Along these ranges, the mean annual temperature varies from 5.2 (Monte
190 Bondone, Italy) to 14.3 °C (Mitra, Portugal) with mean annual precipitation rates
191 from 520 (Bugac-Puszta, Hungary) to 1271 mm (Dripsey, Ireland). With respect to
192 management, the dataset covers the gradient from semi-natural to intensively
193 managed mixed grass species swards (in the presence of clover) and essentially
194 includes vegetation types representative of the zone. Semi-natural grasslands are
195 typified by extensive systems either grazed (with a stocking rate of ~0.5-1.0 LSU ha⁻¹
196 yr⁻¹) or not grazed (where forage production is limited to one cutting per year).
197 Otherwise, the other sites are intensively managed by grazing and/or cutting and are
198 supplied with relative large amounts of N fertilizer (>200 kg N ha⁻¹). It should be
199 noted that the distinction between extensive and intensive grasslands may not be
200 clear-cut. For instance, the unfertilized site of Amplero, grazed by a limited number of
201 livestock units (0.5 LSU ha⁻¹ yr⁻¹), qualifies as an intensive production system because

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5 202 it is grazed for a long period of time in the year (200 days), with intensive utilization
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8 203 of the sward and gain of N from returns by animals. At Easter Bush, the low impact of
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10 204 grazing pressure (in number of animals and duration) is instead compatible with an
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12 205 extensive system because the N fertilization treatment does not exceed the threshold
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14 206 ($>200 \text{ kg N ha}^{-1}$) conventionally set for intensively managed grasslands (e.g. Bos et
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17 207 al., 2005).

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20 208 Monthly and yearly summaries for the average temperature and total precipitation
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22 209 were obtained from the hourly weather data available for each site. The yearly
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24 210 reference evapotranspiration (ET_0 , mm) was also calculated, using the
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27 211 Penman–Monteith method, which uses an hourly time step (Allen, 2005). These
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30 212 weather summaries were the basis for calculating two bioclimatic indicators.

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33 213 The aridity pattern (Fig. 1, right) is characterized by semi-arid to humid conditions,
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35 214 with the average value of De Martonne-Gottmann index (b) ranging from 10-20 at
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37 215 Mitra (Portugal) and Bugac-Pusztá (Hungary) to 45 at Dripsey (Ireland). The climate
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39 216 of Mitra is typically warm and dry for a large part of the year, with hot summers.
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41 217 Bugac-Pusztá represents a continental climate, with hot summers, rain showers and
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43 218 mildly cold winters. The site is characterized by annual water deficit, as well as the
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45 219 Mediterranean upland site of Amplerò (Central Italy). The other sites are mostly
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47 220 humid, with values of the aridity index around 30-50.
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55 222 **2.2 Flux measurements**

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59 223 Each study site was equipped with an eddy covariance system to determine the net
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5 224 ecosystem exchange (NEE) of CO₂. For each site, details of the materials and
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7 225 software used are provided by published papers (Table 1). The eddy covariance
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10 226 system consisted of a fast response 3D sonic anemometer coupled with fast CO₂-H₂O
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12 227 analyzers measuring fluxes of CO₂, latent and sensible heat, and momentum fluxes
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15 228 every 30 minutes. The flux data used in this study were downloaded from the
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17 229 European Fluxes Database Cluster (<http://www.europe-fluxdata.eu>). These data,
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20 230 previously filtered(quality checking and gap-filling) using methods based on friction
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22 231 velocity (u* filtering), contain inherent uncertainty (as detected by bootstrapping
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25 232 approach, after Reichstein et al., 2005 and Papale et al., 2006). We acknowledge that
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28 233 the random and systematic errors of eddy flux measurements could induce uncertainty
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30 234 and affect interpretation of data when eddy flux data were used for model calibration
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32
33 235 and validation (Lasslop et al., 2008). Random errors caused by poor measurement and
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35 236 sampling variability can be quite large at half-hourly time resolution, while systematic
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38 237 errors (biases) can be corrected (Aubinet et al., 2012). It is known that the correction
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41 238 can be insufficient to avoid propagation of uncertainties in the gap-filling procedure
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44 239 and in the partitioning of C exchanges into assimilation and respiration (Richardson et
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46 240 al., 2012). However, the absolute uncertainty in half-hourly measurements is reduced
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49 241 (down to ~10%) with daily or higher (monthly to annual) timescales and often equals
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51 242 the inter-annual variability of the measured fluxes (Hagen et al., 2006; Desai et al.,
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54 243 2008; Kroon et al., 2009).

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59 **2.3 Model description**
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Version preprint

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5 246 The Pasture Simulation model (PaSim, version 5.3,
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7 247 <https://www1.clermont.inra.fr/urep/modeles/pasim.htm>) simulates C and N cycling in
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10 248 grassland ecosystems (mixed swards) at a sub-daily time step. The model has evolved
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13 249 over time, starting as a simulator of dry matter production and associated flows of C,
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15 250 N and water in productive pastures (Riedo et al., 1998). The biological N fixation by
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18 251 clover is simulated by assuming that clover fraction in the sward is fixed for the
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20 252 specific location (after Riedo et al., 1998). PaSim was later improved by Schmid et al.
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23 253 (2001b) with respect to the production and diffusion of N₂O (Riedo et al., 2002) the
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25 254 exchange of NH₃ with the atmosphere by Vuichard et al. (2007a, b), the animal
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28 255 herbage selection and intake, and the effects of diet quality on the emissions of CH₄
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31 256 from grazing animals. More recently, Graux et al. (2011) further improved
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33 257 functionalities to estimate the forage production and dry matter intake taking into
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36 258 account selective grazing between vegetation compartments and the effect of high
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38 259 temperatures on animals, while also simulating ruminant performance and enteric
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41 260 CH₄ emissions during grazing according to the energy content of the intake. The
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44 261 livestock system considers change in body weight of the grazing livestock and
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46 262 simulates the level of milk and meat production with heifers, dairy and suckler cows
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49 263 during the grazing period.
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51 264 The model consists of five interacting modules: microclimate, soil, vegetation,
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54 265 herbivores and management. The soil biophysical module simulates soil temperature
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56 266 and moisture profiles for different soil layers based on soil physical properties and
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59 267 hourly weather inputs and simulated plant water use. The soil biogeochemical module,

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5 268 adapted by monthly time-step CENTURY's organic decomposition approach (Parton,
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7 269 1988), evenly distributes litter into the whole soil profile. The litter is segregated into
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10 270 its structural and substrate components, respectively supplying the structural and
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12 271 metabolic soil pools. In addition, the soil organic matter is further separated into three
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15 272 compartments (active, slow and passive) according to different decomposition rates.
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18 273 Soil pools are interlinked to represent C and N first-order kinetics. The N cycle
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20 274 considers N inputs to the soil via atmospheric deposition, fertilizer addition, symbiotic
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22 275 fixation by legumes and animal faeces and urine. The inorganic soil N is available for
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25 276 root uptake and is lost through the processes (leaching, volatilization and
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27 277 nitrification/denitrification) leading to N₂O and N₂ emissions to the atmosphere. The
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29 278 vegetation module estimates the assimilated C by photosynthesis and allocates it
30
31 279 dynamically to one root and three shoot compartments, each of which consisting of
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33 280 four age classes. The transition from one age category to the next is done using
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35 281 threshold time values to calculate the age of biomass in a compartment from the input
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37 282 of younger material and the loss of older material. C losses from the system are
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39 283 through animal milking, enteric CH₄ emissions and from animal returns, and
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41 284 ecosystem respiration. Accumulated aboveground biomass is either cut or grazed, or
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43 285 enters a pool after senescing. Herbivores are considered during the time they were at
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45 286 pasture (not during indoor periods). Management includes organic and mineral N
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47 287 fertilizations, mowing and grazing, setting by the user or optimized within the model
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49 288 to achieve some objectives.
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5 290 **2.4 Parameterization and Simulation**
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10 292 **2.4.1 Parameterization strategies**
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12 293 In previous studies (Calanca et al., 2007; Vuichard et al., 2007b), PaSim was

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14 294 evaluated for a temporary grassland at Oensingen (Switzerland) and an upland

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17 295 permanent grassland at Laqueuille (France) based on a set of 26 parameters (Table 3).

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19 296 We assumed that a common set of eco-physiological model parameters can be

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22 297 established to simulate C₃ grasslands (including grasses, forbs and legumes) under

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25 298 contrasting climate and management regimes in Europe, while site-specific climate

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27 299 and management conditions provide supplementary factors driving the actual

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30 300 production of grasslands. Based on the set of parameters given in Table 3 and

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33 301 sensitivity analysis results (Ben Touhami et al., 2013), the following two steps were

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36 302 carried out to explore the parameter space and identify a common set of

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38 303 eco-physiological model parameters for PaSim. First, the model was run at all sites

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41 304 with two sets of default parameter values: temporary sown grassland (P_temp) and

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44 305 upland permanent grassland (P_perm). Second, manual calibration was carried out for

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46 306 these parameters, which were identified as influential parameters by Ben Touhami et

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49 307 al. (2013). The values of some of these parameters were modified within their

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52 308 plausible ranges (as from the published literature, documented by Graux, 2011) to

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55 309 ensure realistic representation of a variety of outputs. The calibration work was

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58 310 performed at all study sites together through a trial-and-error process comparing the

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61 311 model predictions with observational data. The solutions obtained constitute a

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5 312 satisfactory performance for all output variables according to the metrics of Table 4.
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7 313 Even though optimization methods are available (Trudinger et al., 2007; Wang et al.,
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9 314 2009), the manual calibration is useful for modellers to get a reference parameter set
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11 315 reflecting expert knowledge and simple adjustment strategies. It was proven that
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13 316 optimization methods may be problematic in confronting the interaction between
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15 317 parameters of complex models (Hollinger and Richardson, 2005; Richardson et al.,
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17 318 2010). The model performance was evaluated for each site separately and with all
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19 319 sites combined, by comparing the simulated C and water fluxes with data from eddy
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21 320 flux towers.
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322 **2.4.2 Model simulation and evaluation**

323 For each site, simulations were carried out with three sets of parameter values
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35 324 described above for all available years in each site
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38 325 PaSim was initialized via a spin-up process using the current weather input. In
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40 326 particular, soil C pools were initialized to steady-state by running the model over 100
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42 327 years by looping the available meteorology at each site following Lardy et al. (2011).
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44 328 The results of the spin-up process matched the supplied soil C measurements with a
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46 329 relative error of about 10% on average ($\pm \sim 2\%$ standard error).
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51 330 The agreement of model outputs against the following five plant and soil variables
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53 331 was examined, gross primary productivity (GPP, $\text{kg C m}^{-2} \text{d}^{-1}$), ecosystem respiration
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55 332 (RECO, $\text{kg C m}^{-2} \text{d}^{-1}$), net ecosystem exchange (NEE, $\text{kg C m}^{-2} \text{d}^{-1}$), soil water content
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57 333 ($\text{m}^3 \text{m}^{-3}$) and actual evapotranspiration (ET, mm d^{-1}). Ecosystem respiration (RECO)

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5 334 plays an important role in estimating global C balances of terrestrial ecosystems, and
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7 335 its knowledge is required to assess the GPP of such ecosystem (as a sum of NEE, and
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9 336 RECO, equations in appendixes A, B, C and D). Soil water content (SWC) and soil
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11 337 temperature (ST) were estimated for each of the six layers that make up the soil
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13 338 profile in PaSim (equations in appendixes E and F).
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15 339 Different performance indices and threshold criteria (Bennett et al., 2013) were used
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17 340 to evaluate the model (Table 4). In particular, the goodness-of-fit R^2 (coefficient of
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19 341 determination) was calculated to assess the linear dependence between modelled and
20
21 342 observed data and the variance explained by the model. The modelling efficiency
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23 343 (ME), the index of agreement (IA) and the root mean square error (RMSE) were
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25 344 derived to assess quantitative differences. The mean bias (MB) is a measure of the
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27 345 overall tendency of the model to under- or over-estimate (the systematic error) the
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29 346 observations. The performance of the model was assessed on daily, weekly and
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31 347 monthly time scales.
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5 **349 3. Results**
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8 350 This section first describes the study sites. Then, the comparison between PaSim
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10 351 results obtained with three sets of parameter values (two previously established and
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12 352 one established in this study) and observed C and water fluxes is illustrated. The
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15 353 model improvement gained with the new parameterization is presented. As well, the
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17 354 impact of both site-specific characteristics and management options on model
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20 355 performances is illustrated, followed by a detailed analysis of the model performances
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22 356 with focus on C and water balances. Only exemplary results (selected output variables
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25 357 and sites) are reported graphically and the main outcomes discussed hereafter, while
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27 358 the full set of results is provided online supplementary material.
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33 360 **3.1 The improvement of the model performance with the redefined parameter**
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35 361 **values**
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38 362 The adjusted parameters (denoted P_{new}) essentially reflect that previously used at
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41 363 the permanent grassland site of Laqueuille (P_{perm}) (Table 3). This indicates that
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43 364 Laqueuille site resembles the European grasslands used in this study, with the
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46 365 exception of four parameters: light-saturated leaf photosynthetic rate for reproductive
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48 366 stage, light-saturated leaf photosynthetic rate for vegetative stage, maximum specific
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51 367 leaf area, and temperature dependence factor of the soil respiration. Even though a
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53 368 formal sensitivity analysis was not undertaken in this study, these parameters had a
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55 369 significant impact on model outputs in a previous study (Ben Touhami et al., 2013).
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58 370 For three parameters, the new values lie between those in the previous studies. For the
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5 371 parameter governing soil respiration, previous modelling studies supported a default
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7 372 value equal to 2, which was substantially decreased (down to 0.7) to obtain simulated
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10 373 respiration values closer to observations. Given its impact on the modelled RECO,
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12 374 characterization of this parameter will require further studies.

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15 375 The estimation of GPP and RECO was improved (Fig. 2) with the redefined common
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17 376 set of eco-physiological parameters (Table 3). GPP was overestimated at all sites
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19 377 using the P_temp parameter set with the exception of Oensingen (the site where that
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21 378 parameter set was originally derived) and, to a lesser extent, of Amplero. Using
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23 379 P_perm parameter set (permanent grassland), the bias of GPP was reduced at seven
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25 380 out of 12 sites. Applying the redefined P_redif parameter set (Table 3), the bias of
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27 381 GPP was further reduced for most of the sites except Oensingen, Bugac-Pusztas and
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29 382 Amplero (Fig. 2).

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33 383 With both P_temp and P_perm parameter sets, RECO was overestimated for most of
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35 384 the sites, with the exception of Oensingen and Amplero (Fig. 2). With P_perm, a
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37 385 slight underestimation was also obtained at intensively-managed Laqueuille (Fig. 2).
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39 386 When the redefined parameter set was used, the bias of RECO was reduced at all sites
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41 387 but Oensingen and Amplero. Overall, the estimated ET has a good agreement with the
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43 388 observed values with no real improvement with the redefined parameter values (Fig. 2
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45 389 and Fig. A1).

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56 391 **3.2 The site variability of model performances with the redefined parameter**
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5 393 Model performance in predicting GPP, RECO and ET (data aggregated on a weekly
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7 394 basis) is closely linked with site-specific conditions such as soil moisture (e.g. dry
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10 395 sandy soils versus humid soils). The model simulated well GPP and RECO for nine
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12 396 out of 12 sites. The exceptions were the sites of Amplero, Mitra and Bugac-Puszt
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14 397 (Fig. 3, Fig. 4 and Table 5), which are characterized by drier conditions than the other
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16 398 sites. The R^2 for the estimated versus observed GPP was greater than 0.8 for most of
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18 399 the sites and was lower than 0.5 at Amplero only ($R^2=0.40$) (Fig. 3). Similar results
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20 400 were found when other indices, such as the slope of the regression, IA, ME and
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22 401 RMSE were taken into account (Table. 5). Compared with GPP estimations, similar
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24 402 model performances were found for RECO across sites, but R^2 values for RECO were
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26 403 relatively lower than those obtained when simulating GPP. For RECO, R^2 values were
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28 404 generally greater than 0.7 for most of the sites, but lower than 0.5 at Amplero
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30 405 ($R^2=0.39$) and Mitra ($R^2=0.46$) (Fig. 4). At Oensingen, the model underestimated
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32 406 RECO during winter time and there were also periods (e.g. 2007) when summer
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34 407 modelled RECO was below of that measured (Fig. 5). However, winter RECO
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36 408 underestimation was common to most of the sites (online supplementary material).
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38 409 The model performance was satisfactory for predicting ET at most of the sites.
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40 410 Exceptions were dry sites such as Amplero, Bugac-Puszt and Mitra (Fig. A1).
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54 412 **3.3 The impact of site characteristics and management practices**

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56 413 Site characteristics and management practices were observed to have an important
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58 414 impact on the model ability to estimate RECO (Fig. 6), but they were less important
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5 415 when predicting GPP, NEE, ET, and soil temperature (data not shown). Concerning
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7 416 management practices, the model tended to underestimate or overestimate RECO,
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9 417 respectively for intensively and extensively managed grasslands (Fig. 6). The
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11 418 occurrence of cutting or grazing had no significant impact on the model performance
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13 419 in predicting RECO. The model tended to slightly underestimate RECO for
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15 420 temporary-sown grasslands, while simulations of permanent grasslands were in good
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17 421 agreement with measured data (Fig. 6). Concerning site-specific conditions, RECO
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19 422 was underestimated for non-montane grasslands (<800 m a.s.l.) and overestimated for
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21 423 mountain sites (Fig. 6).

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28 424 An analysis of the normalized residuals (where each residual is the difference between the
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30 425 predicted and observed values divided by the standard deviation) showed seasonal patterns, which
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32 426 differed by site (Fig. 7). On average, the model slightly underestimated weekly-aggregated RECO
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34 427 in winter in most sites, but significantly overestimated it in summer time on Laqueuille extensive,
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36 428 Monte Bondone, Alinya, Bugac-Pusztta, and Cabauw (Fig. 7). However, most of the residuals fall
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38 429 within the upper limit of the 95% confidence interval.
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46 431 **3.4 C and water balances**

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48 432 The mean annual C fluxes (NEE, GPP and RECO) are meant as a synthesis and a
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50 433 complement to the model performances of PaSim presented in this study. They
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52 434 showed a good agreement with observations using the redefined parameter set (Fig. 8).
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54 435 With these parameter values, the estimated NEE flux was on average $213 \text{ g C m}^{-2} \text{ yr}^{-1}$,
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56 436 which indicates a sink of C approaching the average NEE flux observed at the studied
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5 437 sites ($185 \text{ g C m}^{-2} \text{ yr}^{-1}$) (Fig. 8). The estimated yearly average values of GPP (1220 g
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7 438 $\text{C m}^{-2} \text{ yr}^{-1}$) and RECO ($1006 \text{ g C m}^{-2} \text{ yr}^{-1}$) are in agreement with the observed mean
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10 439 values ($1230 \text{ g C m}^{-2} \text{ yr}^{-1}$ for GPP and $1046 \text{ g C m}^{-2} \text{ yr}^{-1}$ for RECO) across all sites
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12 440 (Fig. 8). As a consequence, the model overestimated the C sink by 15%. This is
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14
15 441 mainly due to RECO, which is underestimated while GPP is in good agreement with
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17 442 observations. The average value of simulated ET (415 mm yr^{-1}) for all sites and years
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20 443 was close to the average value of the observations (451 mm yr^{-1}), which corresponded
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23 444 to an underestimation by 8% (Fig. 9).
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5 446 **4. Discussion**
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10 448 **4.1 Model performance over European grasslands**
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12 449 By evaluating PaSim at a variety of European sites, an improvement of model
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14 450 performances was obtained with using a common set of parameter values to estimate
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17 451 C and water fluxes at weekly and yearly time scales (Fig. 2, Fig. 8 and Table 3). The
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19 452 discrepancy between the observed and estimated GPP and RECO values was reduced
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22 453 compared with previous studies making us of parameter values obtained at specific
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25 454 conditions (Calanca et al., 2007; Ciais et al., 2010). For instance, Calanca et al. (2007)
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27 455 overestimated GPP of about 50% at Laqueuille (France).
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33 457 **4.2 The spatial variability of the model performance**
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36 458 The agreement between the observed and estimated GPP on arid sites (Bugac-Puszta,
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38 459 Amplero) is not as good as on other sites (Fig. 3). The mismatch between observed
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40 460 and estimated GPP values on these dry sites can be partially attributed to the fact that
41
42 461 the model did not simulate soil water content fluctuations during summer time well
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44 462 (see effect of drought conditions for Bugac-Puszta, Fig. 2A and Amplero, Italy, Fig
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46 463 A3). Previous studies confirmed that extreme drought events may have a significant
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49 464 effect on C and water cycles (Ciais et al., 2005; Hussain et al., 2011). With all the
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52 465 slope coefficients less than 1, the range of the simulated soil water content was
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55 466 smaller than the observed range, while the intercept was well above 0 (Fig. A4),
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58 467 indicating that the model overestimated the soil water content during dry periods and
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5 468 underestimated it the rest of time. As a consequence, the overestimated soil water
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7 469 content during drought periods could explain the slight overestimation of GPP (Fig.
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10 470 A2). In contrast, at Mitra (Portugal), the underestimated GPP can be partially
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12 471 attributed to the underestimated soil water content during the growing season (Fig. A5)
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15 472 as water is the limitation factor of plant growth in arid regions. Underestimation of
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17 473 GPP was also obtained at Amplero (Italy), but the incomplete information available
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20 474 for this site (Fig. A3) about starting and ending dates of grazing (constant dates were
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23 475 used) makes interpretation of results difficult.

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25 476 Comparing with GPP, a similar model performance for RECO was found, but R^2 for
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27 477 RECO is relatively lower than GPP (Fig. 3). The lower R^2 for RECO on most of the
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30 478 sites is mainly due to the underestimated RECO during winter as, for instance, at
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33 479 Bugac-Puszta (Fig.7, A2). On one hand the underestimated RECO during winter can
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36 480 be attributed to underestimation of soil temperature in the same period as soil
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38 481 respiration is sensitive to temperature. Soil respiration, one of the main components of
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41 482 RECO, depends on soil moisture, clay content, soil organic matter and C assimilation
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44 483 (Bahn et al., 2008; Balogh et al., 2011; Migliavacca et al., 2011) and these are also the
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46 484 drivers of PaSim. On another hand, the overestimated RECO at Bugac-Puszta is
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49 485 partially due to overestimated GPP as more C substrate is available. A third reason
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52 486 might be that the model overestimated soil moisture content (Fig. A2 and Fig. A5)
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54 487 since soil moisture is one of the most important limiting factors of soil respiration
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56 488 especially in arid and semi-arid regions (Balogh et al., 2011). At Amplero and Mitra,
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59 489 RECO underestimation follows GPP underestimation (Fig. A3 and Fig. A5). Indeed,

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5 490 RECO is intimately related to C supply (Bahn et al., 2008; Migliavacca et al., 2011).
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492 **4.3 Effect of site-specific conditions and management practices**

493 Management practices affect grassland production and greenhouse gas emissions
494 from grassland systems (Schmitt et al., 2010; Zeeman et al., 2010; Luo et al., 2012;
495 Peichl et al., 2012). In this study, PaSim underestimated RECO for
496 intensively-managed grasslands such as Oensingen and Amplero and overestimated it
497 for extensively-managed grasslands (Fig. 6, 7). It is known that intensive management
498 practices can introduce pronounced changes to soil physical structure, which in turn
499 impact the soil water transport processes and the soil heterotrophic respiration
500 (Moyano et al., 2012; Ball, 2013). It is the case for the present study as PaSim did not
501 simulate adequately soil water fluctuations (Fig. 5, Fig. A2 and Fig. A3). At
502 Oensingen (Switzerland), the model did not represent well the soil temperature (Fig. 5.
503 This can be mainly attributed to the disturbance of management, which changed the
504 soil structure when converting cropland into grassland at Oensingen in 2001,
505 considering that tillage changes soil physical structure and, in turn, water and energy
506 transport processes (Acharya et al., 2012). The human management could also modify
507 microbial component and diversity (Cantarel et al., 2012), which significantly impacts
508 on the soil respiration (Allison et al., 2010; Wieder et al., 2013). Moreover, the
509 possibility to introduce more uncertainties is high due to imprecise input management
510 information such as grazing, cutting, and fertilization rate and timing.
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512 **4.4 Limitations and further improvement**

513 Referring to the model performance discussed above, certain modules of PaSim were
514 identified as worthy of further development. One is the soil energy balance module
515 because the model underestimated soil temperature when air temperature was high in
516 summer (Fig. A5) and overestimated soil temperature in winter when air temperature
517 is low (Fig. 5, Fig. A2, Fig. A3 and Fig. A5). The soil water transport module is also
518 critical because soil water fluctuations were not well captured by the model (Fig. 5,
519 Fig. A2, Fig. A3 and Fig. A5), especially on arid and semi-arid grasslands. Moreover,
520 the effect of standing biomass on the energy balance (with shading and albedo) has
521 not been investigated.

522 The choice of eco-physiological parameters used and calibrated manually in this study
523 also requires a forma quantification of the parameter uncertainties introduced in
524 regional studies. The interaction between model parameters is also an issue. For
525 example, specific leaf area (*sla*), which depends on the maximum value set for it
526 (*slam*), interacts in PaSim with C allocation-parameters across different organs of the
527 plant. A higher *sla* could induce a lower allocation of assimilated C to leaf, which may
528 be not the case in reality.

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4 530 **5. Conclusions and perspectives**

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7 532 **5.1 Summary of findings of the regional-scale analysis**

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9 533 A regional-scale analysis of C and water cycles was performed on a variety of
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11 534 European grassland sites using a process-based model (PaSim) with a single set of
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13 535 eco-physiological parameters. It was shown that: 1) variables of C and water cycles
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15 536 (mainly GPP, RECO and ET) can be reasonably simulated by PaSim at European
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17 537 scale using a common set of parameter values; 2) better model performances are
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19 538 obtained at more humid sites; 3) RECO tends to be underestimated in
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21 539 intensively-managed grasslands and overestimated at sites when extensive
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23 540 management practices are adopted.

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25 541 The parameterization for mechanistic simulation of grasslands (with biogeochemical
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27 542 capabilities) is a general way to facing regional studies. We have pursued in this study
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29 543 the question of to what extent calibration can improve the parameterization of a
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31 544 complex grassland model for regional-scale simulations in Europe. Acting upon the
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33 545 most influential parameters of PaSim, we have derived a set of parameter values of
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35 546 general validity in Europe. Even if for specific purposes process-based models need to
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37 547 be parameterized on a site-specific basis, our multi-dataset procedure demonstrates
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39 548 that it is possible to find global estimates for those parameters that encompass a wide
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41 549 range of conditions. The accurate estimation of C and water fluxes relies on the
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43 550 mechanistic representation of key ecosystem processes, with parameters that can be
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45 551 related to physical quantities, thus the perspective of using a regionally calibrated
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47 552 model regulating energy and matter exchanges is more interesting than applying

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5 553 statistical models (Laniak et al., 2013). In addition, statistical model estimations may
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8 554 involve significant levels of collinearity among predictor variables such as
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10 555 temperature and precipitation. They also rely on the assumption of stationarity (e.g.
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12 556 assuming that past relationships will hold in the future, even if factors such as climate
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15 557 and management evolve) and are subject to problems of low signal-to-noise ratios in
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18 558 yield or weather records in many locations (Lobell and Burke, 2010). The main
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20 559 finding is that the satisfactory performance obtained over contrasting climate
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22 560 conditions and management options justify the use of PaSim in regional studies on C
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25 561 and water fluxes in Europe. In C-water flux studies, this is especially relevant when
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28 562 daily-resolution outputs are mainly analysed in temporally-aggregated form - that is,
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30 563 the interest is in weekly, monthly or higher timeframes (e.g. Wallach and Thorburn,
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33 564 2014).

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37 38 566 **5.2 Future work on grassland modelling**

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41 567 Our results indicate further model development is needed to address specific needs
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43 568 and this is critical under the pressure of a changing climate and related extreme
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46 569 weather events, potentially altering the C cycles at different scales (Field et al., 2011).
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49 570 A first issue is that heat waves and dry spells have (favouring conditions of aridity) a
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51 571 direct effect on CO₂ fluxes because warmer temperatures and soil moisture shortage
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54 572 affect both photosynthesis and respiration. Moreover, as changes in seasonal water
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57 573 availability have pronounced effects on individual species, a prominent role is
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59 574 suggested for species interactions in ecosystem responses to climate changes (Suttle et

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5 575 al., 2007). Adaptation and functional biodiversity would dampen down the effect of
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7 576 climate extremes on the C cycle, but the bases for biological adaptation and the role of
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10 577 biodiversity are still unclear (Reichstein et al., 2013b). The use of functional traits of
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12 578 plants, for which plant species are classified into functional types based on vegetative
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15 579 and reproductive traits, proposed by Cruz et al. (2002) can be a promising avenue for
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18 580 future research (Duru et al., 2013). But the level of detail of this study is too low to
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21 581 draw conclusions about the relationship between model parameters and phenotypic
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23 582 traits.

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25 583 To obtain reliable estimates of the sign (source or sink) and magnitude of C-cycle
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28 584 feedbacks, future research should provide a mechanistic basis for inferring effects of
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31 585 extreme meteorological events on the C cycle. This would also help capturing the
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34 586 impacts of drought events on grasslands because drought avoidance of grassland
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36 587 plants mainly depends on rooting depth and soil water reserves. Concepts by Baker et
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38 588 al. (2008) and Sheikh et al. (2009), which consider root access to the stored water in
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41 589 the deep soil water during the drought season, could be integrated into PaSim.

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44 590 The soil temperature module is another area of the model to be improved to better
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46 591 predict soil temperature over winter. This is especially critical for high-altitude
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49 592 grasslands, where vegetative growth restarts at snowmelt. This would also improve
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52 593 the estimation of soil respiration, for which soil temperature is a key driver.

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54 594 Moreover, we acknowledge that the dynamics of aboveground biomass accumulation
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56 595 (either cut for yield production or grazed by animals) were not considered in the study
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59 596 design. Biomass data are mostly discontinuously measured and rather large

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5 597 uncertainties on biomass measurements (mainly owing to spatial heterogeneity) may
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7 598 hinder model evaluation (Vuichard, 2007b). A better model performance (yet
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9 599 integrating biomass measurements) could be attained by optimizing model parameters
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11 600 through model-data fusion methods such as Bayesian calibration (van Oijen et al.,
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13 601 2011). Studies of this type are underway on PaSim (Ben Touhami et al., 2012a, b)
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15 602 with attention given to the interaction among parameters.
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20 603 The improvements of PaSim also include the development of scalable solutions with
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22 604 fundamental plant science research (a broad range of basic impact processes, open to
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24 605 a wide range of plant types) and transition of software engineering technology into
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26 606 modelling practice (Martin et al., 2011; Lardy et al., 2014), while addressing
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28 607 re-usability issues and inter-linking of model components (Donatelli et al., 2012).
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33 608 For managed grasslands, complete management information is often unavailable for
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35 609 regional studies. High-quality grassland management data are needed to better
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37 610 understand their effects on the soil physical structure and C storage (Flechard et al.,
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39 611 2007; Schmitt et al., 2010; Chang et al., 2013).
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43 612 The model improvement actions are ongoing under the guidance and conditions laid
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45 613 down by a number of international projects and initiatives (e.g. AgMIP,
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47 614 <http://www.agmip.org>), and will be expanded by the EU-FP7 project
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49 615 MODEXTREME (<http://modextreme.org>).
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5 617 **Acknowledgments**
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7 618 The results of this research were obtained within an international research project
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9 619 named “FACCE MACSUR – Modelling European Agriculture with Climate Change
10
11 620 for Food Security, a FACCE JPI knowledge hub”. The data used were obtained with
12
13 621 the support of EU projects CarboEurope–IP (FP6 GOCE-CT-2003-505572) and
14
15 622 CARBO-Extreme (FP7-ENV-2008-1-226701). We thank Partner Institutions for
16
17 623 providing grassland data. We also acknowledge technical support from the European
18
19 624 Fluxes Database Cluster (<http://www.europe-fluxdata.eu>). Several reviewers and the
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21 625 editors helped considerably in improving the manuscript.
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4 **627 APPENDICES**

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6 **628 Appendix A - Primary production**

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8 629 Gross primary production (GPP) is the rate at which the plant captures and stores a
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10 630 given amount of chemical energy as biomass in a given length of time. Some fraction
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12 631 of this fixed energy is used for cellular respiration and maintenance of existing tissues
13
14 632 (growth respiration and maintenance respiration). The remaining fixed energy (as
15
16 633 mass of photosynthate) is referred to as net primary production (NPP):

17
18 634
$$NPP = GPP - R_{pl,tot} \quad (1)$$

19
20 635 where $R_{pl,tot}$ is the total plant respiration (autotrophic).

21
22 636 Plant residues deposited to the soil are subject to biological degradation. During this
23
24 637 process, soil organic C is respired to CO₂ while providing energy to the decomposers
25
26 638 (microorganisms and soil fauna). Heterotrophic C fluxes can also include respiratory
27
28 639 losses of CO₂ by grazing ruminants. The combined autotrophic and heterotrophic
29
30 640 ecosystem respiration (RECO) is the CO₂ release from the plants ($R_{pl,tot}$), soil (R_{soil})
31
32 641 and animals (R_{an}). The ensemble of instantaneous inward and outward flows of C
33
34 642 within the ecosystem is the Net Ecosystem Exchange (NEE), given by:

35
36 643
$$NEE = RECO - GPP \quad (2)$$

37
38 644 with positive values indicating the system is a source of C losses, and negative values
39
40 645 indicating that the system sequesters C from the atmosphere.

41 646

42 **647 Appendix B - Total plant respiration**

43
44 648 A single process of respiration is associated with growth (Thornley, 1998). A
45
46 649 component of this respiratory flux is deemed to be maintenance respiration (generally
47
48 650 associated with the re-synthesis of degrading tissue), while also taking into account
49
50 651 the energy required for mineral uptake. The dependence of respiratory components on
51
52 652 C substrate supply is represented by separating C substrate from structure and
53
54 653 coupling the respiration flux to photosynthesis. This allows simulating variation in the
55
56 654 fractions of total plant respiration associated with different processes during plant
57
58 655 development.

59 656 Total plant respiration, $R_{pl,tot}$ (kg C m⁻² d⁻¹), is given by:

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4 657 $R_{pl,tot} = R_{m,rt} + R_{m,sh} + R_{G,rt} + R_{G,sh} + R_N$ (3)
5

6 658 R_G and R_m stand for growth and maintenance respiration, respectively, referred to
7
8 659 shoot (index *sh*) and root (index *rt*). R_N is the respiratory flux associated with uptake
9
10 660 of N from the soil solution. The terms $R_{m,rt}$, $R_{G,rt}$ and R_N are soil respiratory fluxes
11
12 661 from the biological activity of roots (autotrophic soil respiration).
13

14 662

15
16 663 *Growth respiration rates*

17
18 664 The two respiration fluxes needed to produce energy for the growth of shoots and
19
20 665 roots, $R_{G,sh}$ and $R_{G,rt}$ (kg C m⁻² d⁻¹), respectively, are calculated as:

21
22 666 $R_{G,sh} = I_{C,G_{sh}} \cdot \left(\frac{1}{Y_{G,pl}} - 1 \right)$ (4)
23

24
25 667 $R_{G,rt} = I_{C,G_{rt}} \cdot \left(\frac{1}{Y_{G,pl}} - 1 \right)$ (5)
26

27 668 The term $1/Y_{G,pl}$ is an efficiency measure representing the kg of C required to create 1
28
29 669 kg of structural C, $Y_{G,pl}$ being the photosynthetically-assimilated C initially allocated
30
31 670 to substrate C reserves and then used for growth and maintenance of tissues. For the
32
33 671 fraction required for growth, growth rates (kg C m⁻² d⁻¹) are calculated for
34
35 672 aboveground ($I_{C,G_{sh}}$) and belowground ($I_{C,G_{rt}}$) biomass, based on allocation values
36
37 673 occurring during the vegetative stage ($I_{C,G_{sh,veg}}$ and $I_{C,G_{rt,veg}}$, kg C m⁻² d⁻¹), modified in
38
39 674 favour of aboveground biomass during the reproductive stage. The coefficient $Y_{G,pl}$ is
40
41 675 set equal to 0.75 to represent plant growth efficiency (kg C (kg C)⁻¹).
42

43
44 676 C allocation fluxes into roots ($I_{C,G_{rt}}$) and aboveground ($I_{C,G_{sh}}$) plant parts are as
45
46 677 follows:
47

48 678 $I_{C,G_{rt}} = I_{C,G_{rt,veg}} - f_{devstage} \cdot I_{C,G_{rt,veg}}$ (6)
49

50 679 $I_{C,G_{sh}} = I_{C,G_{sh,veg}} + f_{devstage} \cdot I_{C,G_{rt,veg}}$ (7)
51

52 680 Where $f_{devstage}$ is a factor depending on the plant development stage.

53
54
55 681 The terms $I_{C,G_{sh,veg}}$ and $I_{C,G_{rt,veg}}$ are calculated on a constant growth rate at 20 °C ($I_{C,G20}$,
56
57 682 usually set equal to 150 kg² (kg C)⁻¹ (kg N)⁻¹), applied to the cumulative structural
58
59 683 biomass of roots and shoots (W_{sh} , W_{rt} , kg DM m⁻²) and modulated by factors of
60

684 temperature ($f_{T,G}$) and substrate C and N concentrations in shoots and roots (C_{sh} , C_{rt} ,
 685 kg C (kg DM)⁻¹; N_{sh} , N_{rt} , kg N (kg DM)⁻¹), as follows:

$$686 \quad I_{C,G_{sh,veg}} = I_{C,G20} \cdot f_{T,G} \cdot C_{sh} \cdot N_{sh} \cdot W_{sh} \quad (8)$$

$$687 \quad I_{C,G_{rt,veg}} = I_{C,G20} \cdot f_{T,G} \cdot C_{rt} \cdot N_{rt} \cdot W_{rt} \quad (9)$$

688 *Maintenance respiration rates*

690 The respiration fluxes to maintain metabolic processes (those that do not result in a
 691 net increase in plant dry matter) of roots ($R_{m,rt}$) and shoots ($R_{m,sh}$) are a function of
 692 substrate C concentration (C , kg C kg DM⁻¹), structural biomass ($W_{sh} \cdot f_{C,sh}$, $W_{rt} \cdot f_{C,rt}$)
 693 and a temperature-dependent stress factor (Table 3):

$$694 \quad R_{m,sh} = \frac{C}{C + K_{C,mai}} \cdot R_{m,sh,temp} \quad (10)$$

$$695 \quad R_{m,rt} = \frac{C}{C + K_{C,mai}} \cdot R_{m,rt,temp} \quad (11)$$

696 where $K_{C,mai}$ is a maintenance respiration parameter, set equal to 0.03 kg substrate C
 697 (kg structural DM)⁻¹ d⁻¹. The terms $R_{m,sh,temp}$ and $R_{m,rt,temp}$ are temporary shoot and root
 698 maintenance respiration, respectively, as follows:

$$699 \quad R_{m,sh,temp} = f_{T,sh} \cdot \sum_{j=1}^4 k_{mai,j,20} \cdot W_{sh,j} \cdot f_{C,sh} \quad (12)$$

$$700 \quad R_{m,rt,temp} = f_{T,rt} \cdot \sum_{j=1}^4 k_{mai,j,20} \cdot W_{rt,j} \cdot f_{C,rt} \quad (13)$$

701 These maintenance respiration factors are transient in nature since they apply to
 702 temporary values. Both shoot and root biomasses are indeed divided into four state
 703 variables representing four age categories ($j=1, \dots, 4$), for which the following values
 704 are given for the maintenance respiration parameter at 20 °C, $k_{mai,j,20}$ (kg C
 705 kg⁻¹ structural C d⁻¹): 0.020 ($j=1$), 0.020 ($j=2$), 0.015 ($j=3$), 0.010 ($j=4$).

706 The terms $f_{C,sh}$ and $f_{C,rt}$ (kg C kg⁻¹ DM) are fractional C content in shoot and root
 707 structural dry matter, respectively (reference values are 0.50 and 0.39, respectively).

708 *N uptake respiration rate*

710 The respiration flux associated with N uptake (R_N , kg C m⁻² d⁻¹) is:

$$711 \quad R_N = k_N \cdot IN_{soil,rt} \quad (14)$$

712 where $IN_{soil,rt}$ (kg Nm⁻²) is the mineral N (NO₃⁻-N and NH₄⁺-N) uptake by the sward,

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4 and k_N is the respiratory cost of N uptake (the reference value being $0.45 \text{ kg C kg}^{-1} \text{ N}$).
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715 **Appendix C – Heterotrophic soil respiration**

716 Apart the biological activity of roots and associated micro-organisms, the flux of CO_2
717 from the soil to the atmosphere is the result of the production of CO_2 from the activity
718 of heterotrophic bacteria and fungi living on litter and in the root-free soil (after
719 Parton, 1988). The soil organic carbon (SOC) pool is divided into five pools with
720 different turnover times ranging from 0.5 to 1500 years. An additional component is
721 given by the amount of C released as exudates (*exu*) from roots into the soil, estimated
722 as a fraction of plant substrate C. The litter in decomposition over the total soil depth
723 splits into its structural and substrate components, supplying the structural (*str*) and
724 metabolic (*met*) soil pools respectively. Other three compartments with different
725 decomposition rates include active (*act*), slow (*slo*) and passive (*pas*) pools of SOC,
726 consisting of the microbial biomass, refractory components of litter and highly
727 humified organic compounds respectively.

728 Total heterotrophic soil respiration, R_{SOC} ($\text{kg C m}^{-2} \text{ d}^{-1}$), is given by:

$$729 R_{SOC} = R_{str} + R_{met} + R_{exu} + R_{act} + R_{slo} + R_{pas} \quad (15)$$

731 *Soil respiration from structural organic matter*

732 The respiration flux associated with structural SOC (R_{str} , $\text{kg C m}^{-2} \text{ d}^{-1}$) is:

$$733 R_{str} = (1 - f_{lig, str}) \cdot f_{r, str} \cdot f_{C, str} + f_{lig, str} \cdot f_{r, str, lig} \cdot f_{C, str} \quad (16)$$

734 The microbial respiration parameter for the decomposition of the structural pool, $f_{r, str}$,
735 and of lignin, $f_{r, str, lig}$, are set equal to 0.55 and 0.3, respectively. The term $f_{lig, str}$ is the
736 fraction of lignin in structural soil organic matter. The fraction of C in the structural
737 plant residue, $f_{C, str}$, is as follows:

$$738 f_{C, str} = k_{str} \cdot W_{C, str} \quad (17)$$

739 where k_{str} ($\text{kg C m}^{-2} \text{ d}^{-1}$) is the decomposition rate for the structural pool and $W_{C, str}$ (kg
740 C m^{-2}) is the C content in structural fraction of plant residue (depending on
741 temperature, lignin, texture and water content).
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4 743 *Soil respiration from metabolic organic matter*

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6 744 The respiration flux associated with metabolic SOC (R_{met} , kg C m⁻²d⁻¹) is:

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8 745 $R_{met} = f_{r,met} \cdot f_{C,met}$ (18)

9
10 746 The microbial respiration parameter for the decomposition of the metabolic pool, $f_{r,met}$,
11 747 is set equal to 0.55. The fraction of C in metabolic pool, $f_{C,met}$ (kg C m⁻²), is calculated
12 748 assuming linear kinetics.
13
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16 749
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18 750 *Soil respiration from exudates*

19
20 751 The respiration flux associated with root exudates (R_{exu} , kg C m⁻² d⁻¹) is:

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22 752 $R_{exu} = f_{r,exu} \cdot f_{C,exu}$ (19)

23
24 753 The parameter $f_{r,exu}$ is set equal to 0.75. The term $f_{C,exu}$ (kg C m⁻²) is C substrate output
25 754 for root exudation.
26
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30 755
31 756 *Soil respiration from active organic matter*

32 757 The respiration flux associated with active SOC (R_{act} , kg C m⁻²d⁻¹) is:

33
34 758 $R_{act} = f_{r,act} \cdot f_{C,act}$ (20)

35 759 The fraction of C in active pool, $f_{C,act}$ (kg C m⁻²), is calculated as follows:

36
37 760 $f_{r,act} = 0.85 - 0.68 \cdot (f_{clay,ah} + f_{silt,ah})$ (21)

38
39 761 where f_{clay} and f_{silt} are fractions of clay and silt, respectively.
40
41

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43 762
44 763 *Soil respiration from slow organic matter*

45 764 The respiration flux associated with slow SOC (R_{slo} , kg C m⁻²d⁻¹) is:

46
47 765 $R_{slo} = f_{r,slo} \cdot f_{C,slo}$ (22)

48 766 The microbial respiration parameter for the decomposition of the slow pool, $f_{r,slo}$, is set
49 767 equal to 0.55. The fraction of C in slow fraction, $f_{C,met}$ (kg C m⁻²), is calculated as
50 768 follows.
51
52

53
54 769 $f_{r,slo} = k_{slo} \cdot W_{C,slo}$ (23)

55
56 770 $k_{slo} = k_{slo,20} \cdot k_{dec,t} \cdot k_{dec,\theta}$ (24)

57
58 771 $W_{C,slo}$ (kg C m⁻²) is the C content in slow pool (depending on temperature, lignin,
59 772 texture and water content). The term $k_{slo,20}$ (d⁻¹) is the turnover rate for slow C pool at
60
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4 773 20 °C, equal to 0.00027. The terms $k_{dec,t}$ and $k_{dec,\theta}$ are factor activities of soil organic
5
6 774 matter for temperature and water content, respectively.

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10 776 *Soil respiration from passive organic matter*

11 777 The respiration flux associated with active SOC (R_{pas} , kg C m⁻²d⁻¹) is:

12
13
14 778 $R_{pas} = f_{r,pas} \cdot f_{c,pas}$ (25)

15 779 The microbial respiration parameter for the decomposition of the passive pool, $f_{r,pas}$, is
16
17 780 set equal to 0.55. The fraction of C in passive pool, $f_{c,pas}$ (kg C m⁻²), is calculated
18
19 781 assuming linear kinetics.

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24 783 **Appendix D - Respiration from grazing animals**

25 784 Half of the C in plant material consumed by grazing animals ($I_{C,veg\rightarrow ani}$, kg C m⁻² d⁻¹)
26
27 785 is assumed to be respired (R_{ani} , kg C m⁻²d⁻¹):

28
29
30 786 $R_{ani} = 0.5 \cdot I_{C,veg\rightarrow ani}$ (26)

31 787 The amount of ingested C is estimated as follows:

32
33 788 $I_{C,veg\rightarrow ani} = (f_{c,sh} + C) \cdot \frac{W_{sh}}{W_{sh,tot}} \cdot I_{veg\rightarrow ani}$ (27)

34
35 789 where ($I_{veg\rightarrow ani}$, kg DM m⁻² d⁻¹) is the amount of ingested dry matter, which increases
36
37 790 with the aboveground plant biomass ($W_{sh,tot}$, kg DM m⁻²) available for the animals
38
39 791 (W_{sh} , kg DM m⁻², is the cumulative structural aboveground biomass), limited by the
40
41 792 maximum ingestion capacity the animal is able to maintain (I_{max} , whose reference
42
43 793 value is 16 kg DM d⁻¹ animal⁻¹).

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4 **795 Appendix E - Soil temperature**

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6 796 The calculation of temperature in each soil layer is based on the energy balance
7
8 797 equations for the different soil layers (Campbell, 1985; Monteith, 1965; Shuttleworth
9
10 798 and Wallace, 1985):

11
12 799
$$T_s^*(h) = 0.6 \cdot T_s(h) + (1 - 0.6) \cdot T_s'(h) \quad (28)$$

13
14 800 Where $T_s(h)$ (K) is the soil temperature at the midpoint of the i^{th} layer in the present
15
16 801 time step, $T_s'(h)$ (K) is soil temperature in the same layer but one time step in the past,
17
18 802 and $T_s^*(h)$ (K) is temperature in the i^{th} layer at some time between the two time steps.

19
20
21 803 **Appendix F - Soil water balance**

22 804 The water content in the different soil layers determines photosynthesis and stomatal
23
24 805 conductance, soil evaporation, and rates of soil biological processes, and is used to
25
26 806 calculate soil temperature in the different layers, which influences belowground plant
27
28 807 processes, soil heat flux, and soil biological processes. Values of the soil matrix
29
30 808 potential in soil layer h , $\psi(h)$ (m), is related to the water content in the same layer,
31
32 809 $\theta_s(h)$ ($\text{m}^3 \text{m}^{-3}$) by the soil moisture characteristic (Campbell, 1985):

33
34 810
$$\theta_s(h) = \theta_{s,sat}(h) \cdot \left[\frac{\psi_e(h)}{\psi(h)} \right]^{\frac{1}{b(h)}} \quad (29)$$

35
36 811 where $\theta_{s,sat}(h)$ ($\text{m}^3 \text{m}^{-3}$) is the saturation soil water content in soil layer h , $\psi_e(h)$ is the
37
38 812 air entry water potential (m) in soil layer h , $b(h)$ is a physical parameter for soil layer
39
40 813 h .

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Tables

Table 1. Location, climate and management of the grassland study sites.

Country	Site	ID	Years	Geographical settings			Climate			Source
				Latitude	Longitude	Elevation(m a.s.l.)	Mean air temperature (°C)	Precipitation total (mm yr ⁻¹)		
France	Laqueuille	FRL.aq1	2004-2010	45° 38' N	02° 44' E	1040	7.8	1072	Klumpp et al. (2011)	
		FRL.aq2	2004-2010							
Germany	Grillenbug	DEGri	2004-2008	50° 57' N	13° 30' E	375	8.5	946	Prescher et al. (2010)	
Hungary	Bugac-Puszt	HUBug	2003-2008	46° 41' N	19° 36' E	140	10.2	520	Pintér et al. (2008)	
Ireland	Dripsey	IEDri	2003-2005	51° 59' N	08° 45' W	195	9.6	1271	Byrne and Kiely (2006)	
Italy	Amplero	ITAmp	2003-2007	41° 52' N	13° 38' E	884	9.4	781	Wohlfahrt et al. (2008)	
		ITMbo	2003-2007	46° 00' N	11° 02' E	1550	5.2	1003	Wohlfahrt et al. (2008)	
Portugal	Mitra	PTMi2	2005-2007	38° 32' N	08° 00' W	190	14.3	627	Aires et al. (2008)	
Spain	Vall d'Alinya	ESVDA	2004-2008	42° 12' N	01° 26' W	1770	6.2	908	Wohlfahrt et al. (2008)	
Switzerland	Oensingen	CHOe1	2002-2009	47° 17' N	07° 44' E	450	9.3	1197	Ammann et al. (2007)	
The Netherlands	Cabauw	NLCa1	2004-2007	51° 57' N	04° 54' W	0.7	10	800	Jacobs et al. (2007)	
United Kingdom	Easter Bush	UKEBu	2002-2008	55° 52' N	03° 02' W	190	9.0	956	Soussana et al. (2007a)	

Table 2. Soil properties and management of the grassland study sites (ID as in Table 1)

ID	Management (average)										Soil properties for the whole soil profile ¹				
	Utilization ² (yr ⁻¹)	Cuts (yr ⁻¹)	Nitrogen fertilization		Grazing			Clover fraction	Soil depth (m)	Soil texture					
			Events (yr ⁻¹)	Total amount (kg N ha ⁻¹ yr ⁻¹)	Stocking rate (LSU ³ ha ⁻¹ yr ⁻¹)	Duration (d yr ⁻¹)	Sand (%)			Silt (%)	Clay (%)	Bulk density (t m ⁻³)			
FRLaq1	Intensive	-	3	210	1.10	160	0.12	0.7	27	53	20	0.87			
FRLaq2	Extensive	-	-	-	0.60	160	-	-	-	-	-	-			
DEGri	Intensive	2-3	-	-	-	-	0.20	0.7	13	79	8	1.06			
BUG	Extensive	-	-	-	0.30	180	0.10	0.6	85	6	9	1.08			
IEDri	Intensive	-	3	280	0.72	150	0.17	0.7	52	27	21	1.19			
ITAmP	Intensive	-	-	-	0.50	200	0.20	0.7	12	33	55	0.92			
ITMbo	Extensive	1	-	-	-	-	0.20	0.7	44	39	17	1.04			
PTMi2	Extensive	-	-	-	1.46	70	0.00	0.7	55	35	10	1.12			
ESVDA	Extensive	-	-	-	0.18	120	0.10	0.6	15	50	35	0.87			
OEN	Intensive	3-4	4	214	-	-	0.25	1.0	24	33	43	1.15			
UKEBu	Extensive	-	4	200	0.65	160	0.00	0.7	12	24	62	1.47			
NLCa1	Intensive	-	3	225	0.60	180	0.00	0.7	45	25	30	1.19			

¹ Soil properties were obtained as the mean of six layers. Simulations make use of basic information for each layer.

² The classification into "extensive" or "intensive" grasslands was based on fertilizing intensity, the number of cuts, cattle density and/or grazing duration, which reflect the socio-economic environment in each country.

³ Livestock Standard Unit: standard measurement unit allowing the aggregation of various categories of livestock (species, sex and age) in order to enable them to be compared, related to the animals' feed requirements, using as a reference unit (=1 LSU) a dairy cow producing 3000 kg of milk annually, without additional concentrated foodstuffs (EC, 2008).

Table 3. Summary of the PaSim eco-physiological parameters considered in this study. For each parameter, three sets of values are reported: two from the calibration obtained in previous studies (P_temp, Oensingen and P_perm, Laqueuille, after Calanca et al., 2007 and Vuichard et al., 2007b) and one from the calibration performed in this study (P_redef). Greyed areas indicate the recalibrated parameters.

Name	Parameters		Values			Description
	Unit	P_temp (Oensingen)	P_perm (Laqueuille)	P_redef		
Fractional C content of root structural dry matter ($f_{C,rt}$)	kg C kg ⁻¹ DM	0.5	0.43	0.43		These parameters multiply the root and shoot growth rates, respectively, to obtain the C substrate variation.
Fractional C content of shoot structural dry matter ($f_{C,sh}$)	kg C kg ⁻¹ DM	0.39	0.435	0.435		
Parameter of the fractional N content of new plant structural dry matter ($f_{N,pl}$)	kg N kg ⁻¹ DM	0.022	0.018	0.018		This parameter is used to derive the nitrogen concentration of newly produced structural dry matter.
Maximum canopy height	m	0.35	0.707	0.707		It determines the canopy height to calculate the latent and sensible heat fluxes from the canopy and the soil surface.
Shoot turnover rate at 20 °C (%)	d ⁻¹	0.03	0.012	0.012		They represent the leaf and root life-spans at a constant temperature, used to calculate the flow of plant residue.
Root turnover rate at 20 °C (%)	d ⁻¹	0.05	0.048	0.048		
Fraction of fibres in ingested ears (NDF_{ear})	-	0.8	0.742	0.742		These parameters represent the proportion of fibre (NDF) in the ingested tissues (ear, lamina, sheath/stem).
Fraction of fibres in ingested blades (NDF_{lam})	-	0.6	0.542	0.542		
Fraction of fibres in ingested stems and sheaths (NDF_{stem})	-	0.7	0.642	0.642		
Maximum plant N concentration ($F_{N,max}$)	kg N kg ⁻¹ DM	0.045	0.03	0.03		This parameter limits N absorption by plant.

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Digestible neutral detergent fibres of leaf blades - age 1 (DNDF _{lam1})	kg digestible fibres kg ⁻¹ fibres	0.92	0.91	0.91
Digestible neutral detergent fibres of leaf blades - age 2 (DNDF _{lam2})	kg digestible fibres kg ⁻¹ fibres	0.82	0.77	0.77
Digestible neutral detergent fibres of leaf blades - age 3 (DNDF _{lam3})	kg digestible fibres kg ⁻¹ fibres	0.76	0.63	0.63
Digestible neutral detergent fibres of leaf blades - age 4 (DNDF _{lam4})	kg digestible fibres kg ⁻¹ fibres	0.74	0.35	0.35
Digestible neutral detergent fibres of stems and leaf sheaths - age 1 (DNDF _{stem1})	kg digestible fibres kg ⁻¹ fibres	0.84	0.92	0.92
Digestible neutral detergent fibres of stems and leaf sheaths - age 2 (DNDF _{stem2})	kg digestible fibres kg ⁻¹ fibres	0.65	0.79	0.79
Digestible neutral detergent fibres of stems and leaf sheaths - age 3 (DNDF _{stem3})	kg digestible fibres kg ⁻¹ fibres	0.53	0.66	0.66
Digestible neutral detergent fibres of stems and leaf sheaths - age 4 (DNDF _{stem4})	kg digestible fibres kg ⁻¹ fibres	0.5	0.4	0.4

These parameters influence the daily amount of digestible neutral detergent fibre (DNDF) from different plant components (ear, lamina and sheath/stem) in the animal's intake, depending on the age of tissues (four classes).

Digestible neutral detergent fibres of ears - age 1 (DNDF _{ears1})	kg digestible fibres kg ⁻¹ fibres	0.76	0.93	0.93	0.93	They represent the influence of developmental stage (the end of ear emergence marking the transition from the reproductive to the vegetative stage) on the light-saturated leaf photosynthetic rate (defined at standard conditions of temperature, atmospheric CO ₂ concentration and plant nitrogen concentration), which is a component of the rate of canopy photosynthesis.
Digestible neutral detergent fibres of ears - age 2 (DNDF _{ears2})	kg digestible fibres kg ⁻¹ fibres	0.48	0.68	0.68	0.68	
Digestible neutral detergent fibres of ears - age 3 (DNDF _{ears3})	kg digestible fibres kg ⁻¹ fibres	0.3	0.44	0.44	0.44	
Digestible neutral detergent fibres of ears - age 4 (DNDF _{ears4})	kg digestible fibres kg ⁻¹ fibres	0.26	0.38	0.38	0.38	
Light-saturated leaf photosynthetic rate for reproductive stage (<i>pmco2rep</i>)	μmol C m ⁻² s ⁻¹	22.6666	16.723	16.723	19.723	This is the maximum value of specific leaf area, defined as the ratio of leaf area to dry weight, used to derive canopy leaf area from leaf biomass.
Light-saturated leaf photosynthetic rate for vegetative stage (<i>pmco2veg</i>)	μmol C m ⁻² s ⁻¹	15	11.099	11.099	13.099	
Maximum specific leaf area (<i>slam</i>)	m ² kg ⁻¹	33.5	25	25	29	It multiplies the temperature-dependent function ¹ to estimate soil respiration.
Temperature dependence factor of the soil respiration (<i>m_{rr}</i>)	-	2	2	2	0.7	

$$f(T_a) = \frac{(T_a - T_0)^{q_{FT}} \cdot (T'_0 - T_a)}{(T_{ref} - T_0)^{q_{FT}} \cdot (T'_0 - T_{ref})}, T_0 \leq T_a \leq T'_0$$

0 otherwise

where T_a (°C) is air temperature; T_0 (°C), T'_0 (°C), T_{ref} (°C) are, respectively, the base air temperature, the ceiling air temperature at which

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processes cease, and reference air temperature at which the maximum rate of respiration occurs; q_{rr} (unitless) is a shape parameter. Reference values for soil respiration are: $T_0=0$ °C, $T_0=45$ °C, $T_{ref}=20$ °C, $q_{rr}=2$.

Table 4. Model performance measurement indices.

Performance measure	Equation	Unit	Value range and purpose	Reliability	
				criterion	source
Coefficient of determination (R^2) of the linear regression estimates versus measurements (Addiscott and Whitmore, 1987)	$R^2 = \frac{\sum_{i=1}^n (P_i - O_i) \cdot (O_i - \bar{O})}{\sqrt{\sum_{i=1}^n (P_i - \bar{P})^2 \cdot \sum_{i=1}^n (O_i - \bar{O})^2}}$	-	0 (absence of fit of the regression line) to 1 (perfect fit of the regression line): the closer the values are to 1, the better the model	>0.8	De Jager (1994)
IA, index of agreement (Willmott and Wicks, 1980)	$IA = 1 - \frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (P_i - \bar{O} + O_i - \bar{O})^2}$	-	0 (absence of agreement) to 1 (perfect agreement): the closer the values are to 1, the better the model	>0.8	De Jager (1994)
RMSE, root mean square error (Fox, 1981)	$RMSE = \sqrt{\frac{\sum_{i=1}^n (P_i - O_i)^2}{n}}$	unit of the variable	0 (optimum) to positive infinity: the smaller RMSE, the better the model performance	-	-
MB, mean bias (Addiscott and Whitmore, 1987)	$MB = \frac{\sum_{i=1}^n (P_i - O_i)}{n}$	unit of the variable	negative infinity (underestimation) to positive infinity (overestimation): the closer the values are to 0, the better the model	-	-
ME, modelling efficiency (Nash and Sutcliffe, 1970)	$ME = 1 - \frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2}$	-	negative infinity to 1 (optimum): the closer the values are to 1, the better the model	>0.5	Moriassi et al. (2007)

Table 5. Model performances across grassland sites (ID as in Table 1) based on different evaluation indices (as in Table 4) calculated on weekly aggregated data.

Site ID	GPP						RECO						ET							
	NEE		RMSE		IA		ME		R ²		BIAS		RMSE		IA		ME		R ²	
	BIAS	RMSE	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²
CHOe1	-6.07	15.83	0.91	0.69	0.73	-10.35	12.90	0.88	0.58	0.88	-1.69	3.14	0.96	0.84	0.891					
ITMbo	-2.22	10.89	0.96	0.85	0.86	0.89	12.22	0.93	0.59	0.86	-1.26	2.67	0.97	0.89	0.926					
DEGri	-0.10	9.13	0.95	0.81	0.83	-1.53	11.74	0.88	0.44	0.63	1.23	3.45	0.92	0.60	0.827					
UKEBu	-1.85	10.53	0.95	0.79	0.81	-2.88	10.44	0.91	0.68	0.72	0.66	3.95	0.82	0.37	0.465					
IEDri	5.03	13.40	0.93	0.66	0.83	2.27	12.58	0.91	0.61	0.70	-1.84	2.65	0.94	0.76	0.887					
HUBug	9.24	16.79	0.83	-0.02	0.64	7.95	15.12	0.80	-0.59	0.70	1.74	6.03	0.86	0.24	0.645					
ITAmp	-9.06	16.18	0.74	0.10	0.40	-9.03	14.44	0.61	-0.07	0.39	-2.31	5.08	0.88	0.57	0.676					
ESVDA	0.94	6.59	0.92	0.58	0.77	1.43	5.04	0.91	0.52	0.82	0.78	2.82	0.95	0.73	0.864					
FRLq1	-2.94	10.07	0.96	0.85	0.87	-2.87	11.42	0.93	0.65	0.80	-4.12	5.93	0.86	0.47	0.728					
FRLq2	5.35	14.84	0.93	0.59	0.85	4.51	13.66	0.90	0.35	0.84	-1.49	3.97	0.94	0.75	0.799					
PTMi2	-3.89	11.21	0.82	0.47	0.53	-2.14	8.39	0.78	0.43	0.46	3.79	8.21	0.61	-2.04	0.316					
NLCa1	4.27	14.04	0.92	0.57	0.80	6.55	16.23	0.88	0.27	0.76	-1.18	2.87	0.96	0.82	0.888					
Site ID	NEE						SWC						SoiIT							
	RMSE		IA		ME		R ²		BIAS		RMSE		IA		ME		R ²			
	BIAS	RMSE	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²	g C week ⁻¹ m ⁻²		
CHOe1	-4.10	12.27	0.80	0.25	0.43	5.04	7.78	0.69	0.21	0.72	-3.19	4.06	0.91	0.71	0.91					
ITMbo	3.11	17.13	0.48	-0.92	0.02	-15.84	16.89	0.41	-5.20	0.26	-0.80	3.88	0.94	0.64	0.89					
DEGri	-1.43	7.72	0.83	0.44	0.50	-4.24	6.23	0.83	0.50	0.80	-3.63	4.35	0.92	0.55	0.94					
UKEBu	-1.03	8.90	0.74	0.21	0.31	1.69	5.36	0.75	0.48	0.68	-3.06	4.00	0.87	0.34	0.82					
IEDri	-2.76	8.03	0.81	0.25	0.47	-1.60	2.64	0.82	0.49	0.72	-1.24	1.73	0.94	0.71	0.93					
HUBug	-1.29	6.27	0.84	0.45	0.52	7.10	8.44	0.55	-1.34	0.34	-0.93	2.06	0.98	0.92	0.96					
ITAmp	0.19	9.81	0.72	0.14	0.27	3.52	7.55	0.70	0.21	0.38	-0.94	5.96	0.90	0.39	0.77					
ESVDA	0.49	6.04	0.65	-0.81	0.19	4.47	6.05	0.68	-0.14	0.48	1.95	2.46	0.97	0.88	0.96					

FRLq1	0.08	9.88	0.76	0.32	0.35	4.45	6.06	0.60	-0.57	0.29	-1.36	2.42	0.96	0.85	0.911
FRLq2	-0.83	9.34	0.76	0.34	0.37	5.03	7.69	0.60	-0.24	0.29	-1.75	2.53	0.95	0.79	0.905
PTMi2	1.75	7.90	0.68	-0.51	0.25	0.28	8.83	0.61	0.39	0.78	-1.45	2.86	0.97	0.91	0.944
NLCa1	2.29	10.68	0.68	-0.79	0.28	-16.50	19.98	0.49	-1.67	0.29	NA	NA	NA	NA	NA

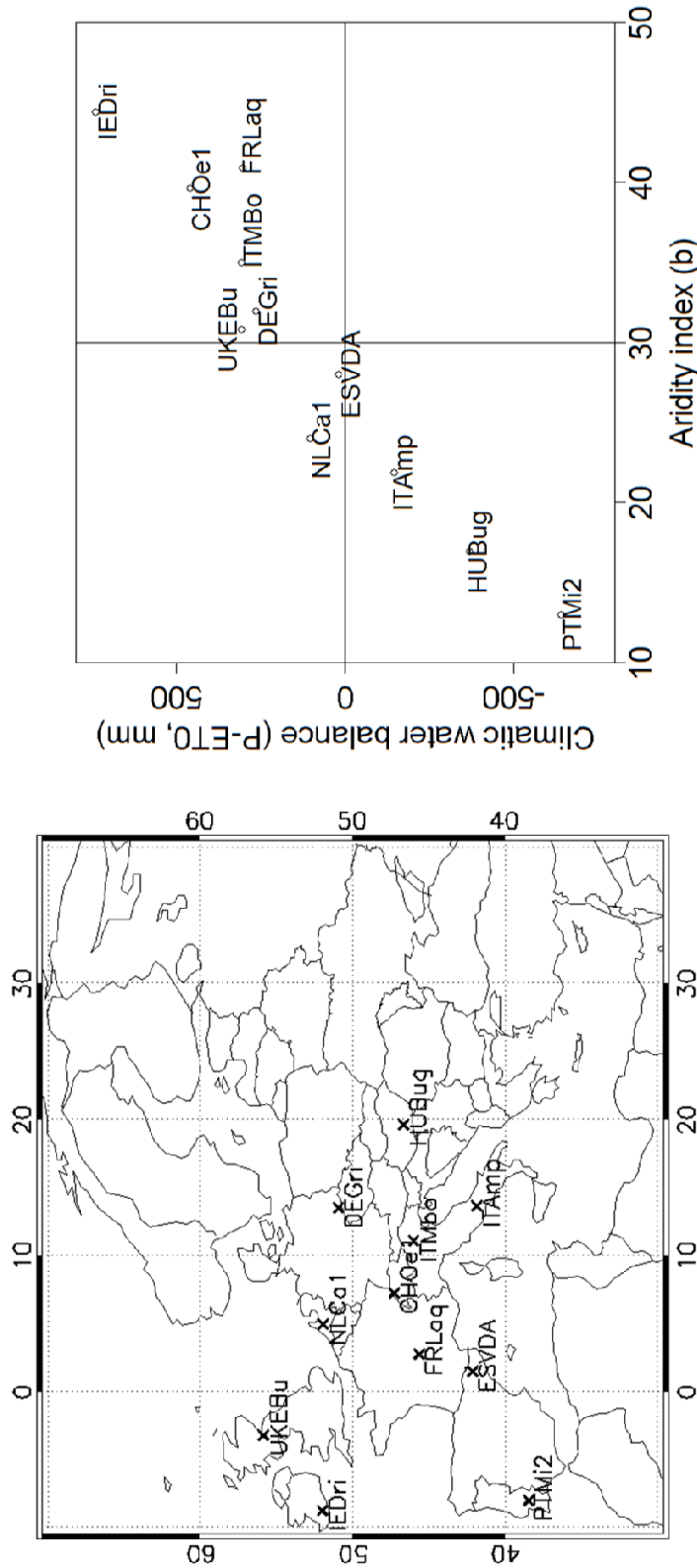


Fig 1. Geographic location (left) and classification (right) of grassland sites (ID as in Table 1) with respect to two indices (climatic water balance and De Martonne-Gottmann aridity index) of water availability. For the aridity index b , (De Martonne, E, 1942), the following range limits discriminate between thermo-pluviometric conditions associated with aridity gradients: $b < 5$: extreme aridity; $5 \leq b \leq 14$: aridity; $15 \leq b \leq 19$: semi-aridity; $20 \leq b \leq 29$: sub-humidity; $30 \leq b \leq 59$: humidity; $b > 59$: strong humidity (Diodato and Ceccarelli, 2004).

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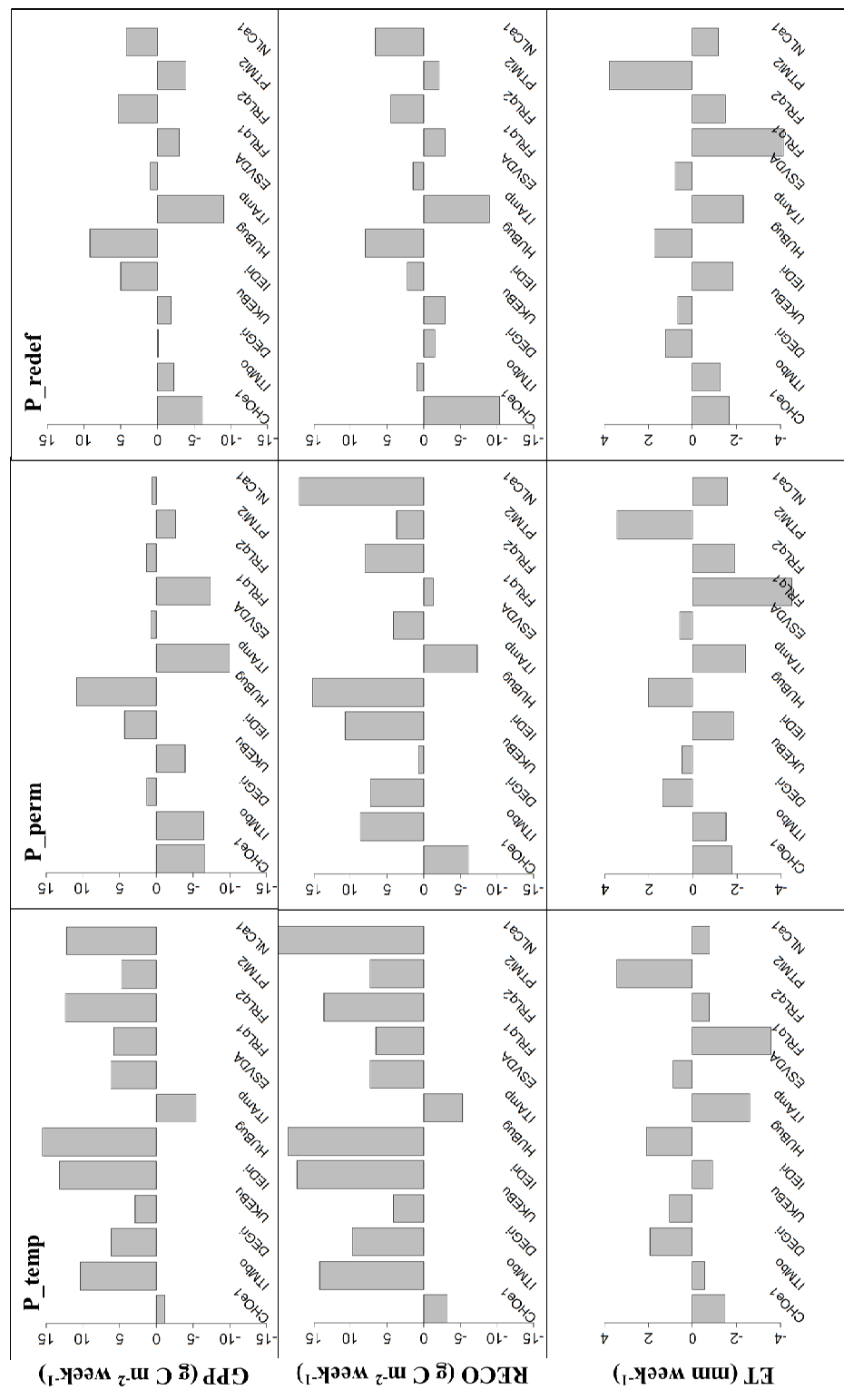


Fig 2. The mean bias of weekly values of GPP, RECO (g C m⁻² week⁻¹) and ET (mm week⁻¹), using three sets of parameter values: for temporary grasslands as established at Oensingen, Switzerland (P_temp, left), for permanent grasslands as established at Laqueuille, France (P_perm, middle), and the common set established in this study (P_redef, right).

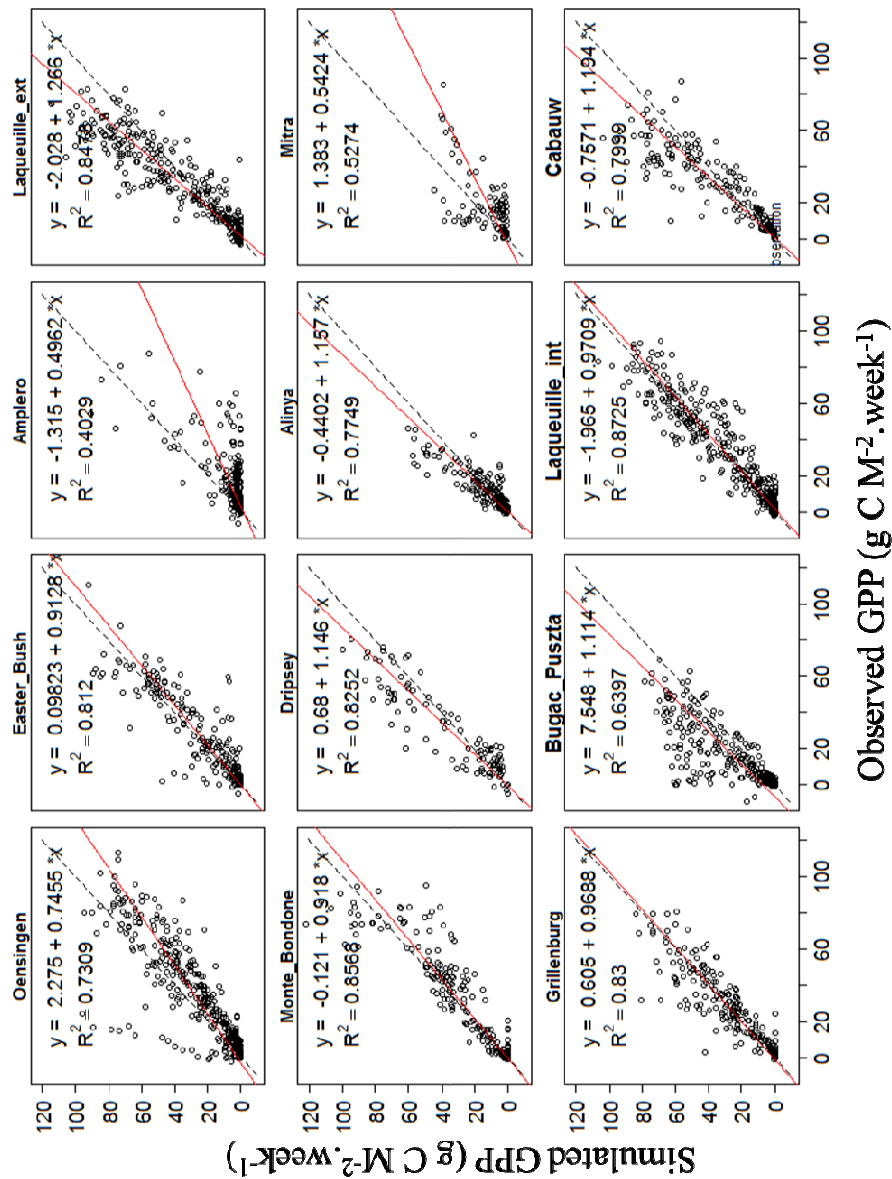


Fig. 3. Scatter plots of simulated versus measured GPP weekly values. The dashed line is the 1:1 line. The solid red line represents the regression equation. The goodness-of-fit R^2 is the coefficient of determination of the regression equation.

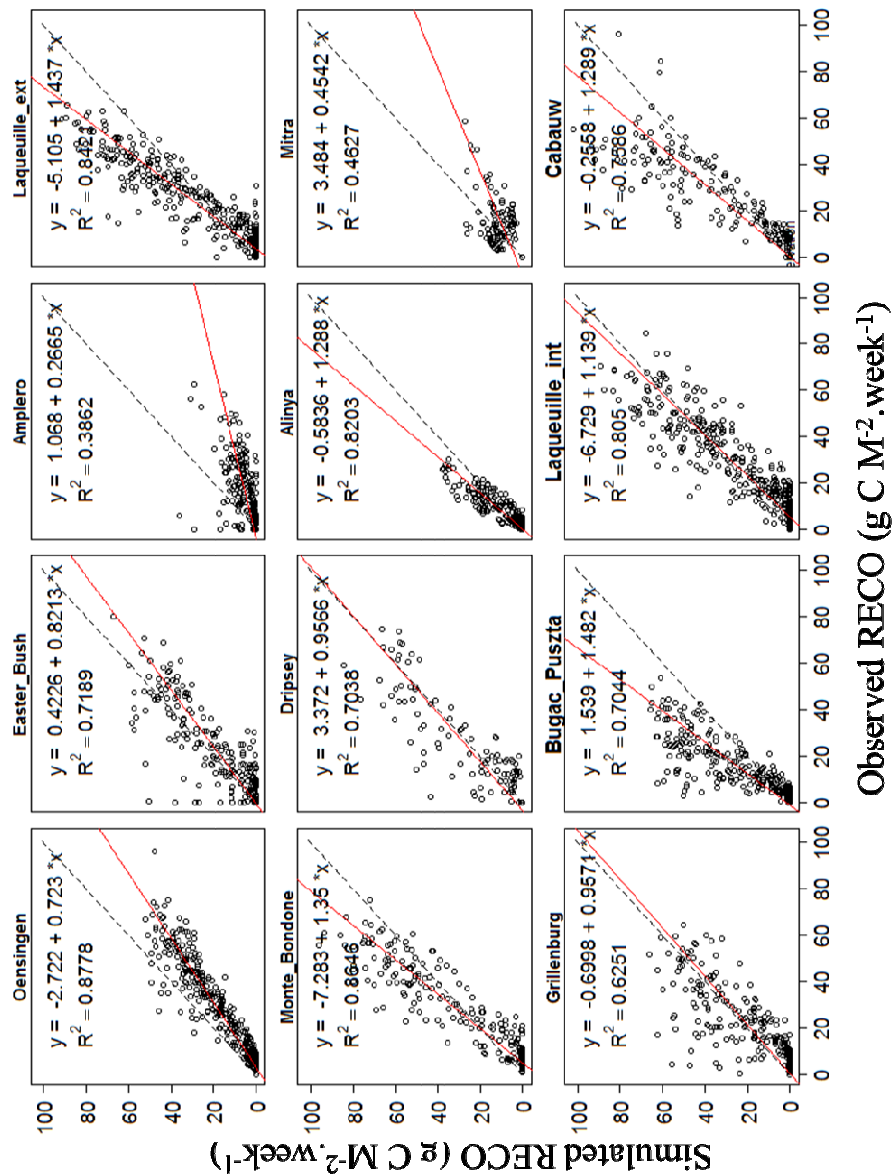


Fig. 4. Scatter plots of simulated versus measured RECO weekly values. The dashed line is the 1:1 line. The solid red line represents the regression equation. The goodness-of-fit R^2 is the coefficient of determination of the regression equation.

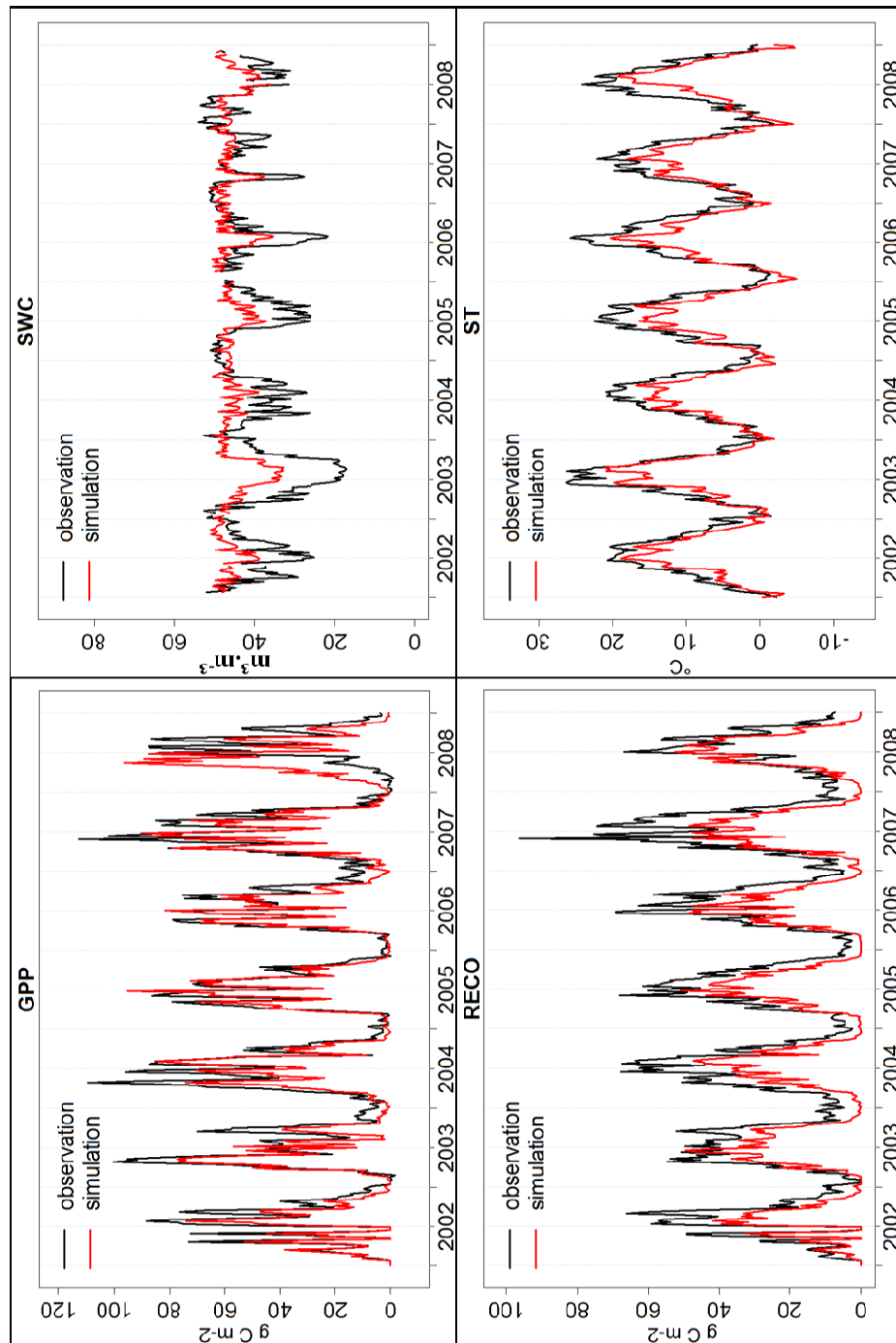
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Fig. 5. The variability of simulated GPP, RECO, soil temperature (ST) and soil water content (SWC) against the observed data for Oensingen (Switzerland) weekly values.

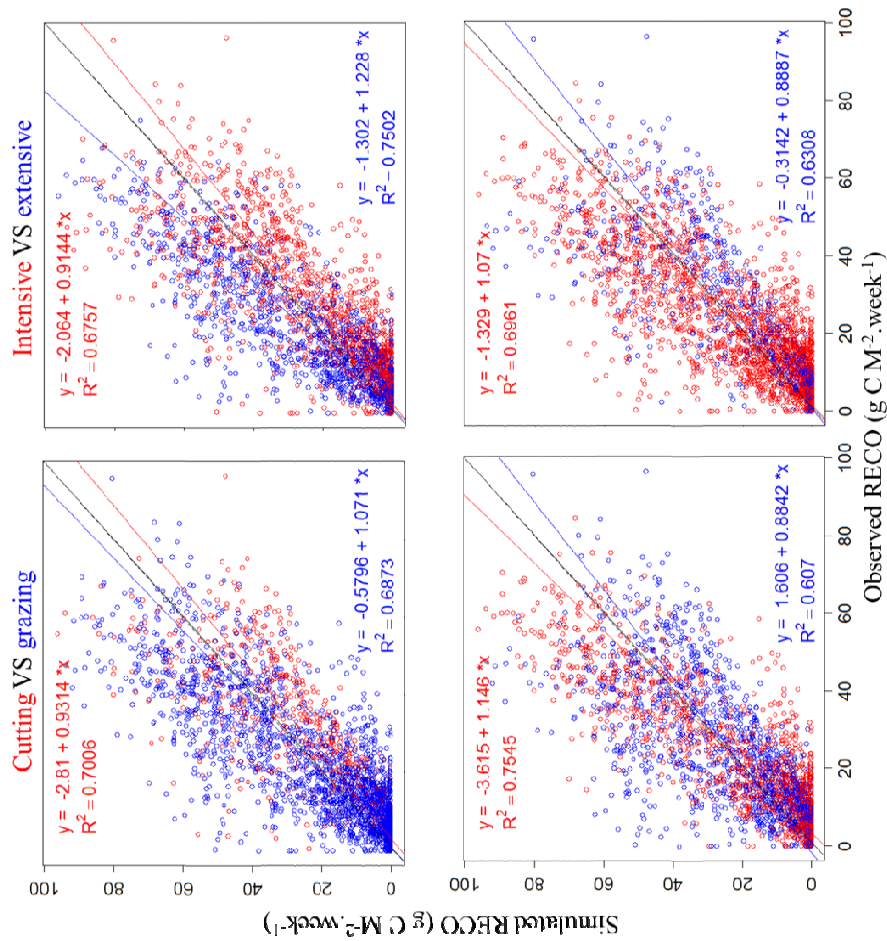


Fig. 6. Scatter plots of simulated with the redefined parameters versus measured RECO values (g C M⁻².week⁻¹) according to site characteristics and management practices. The goodness-of-fit R^2 is the coefficient of determination of the regression equation.

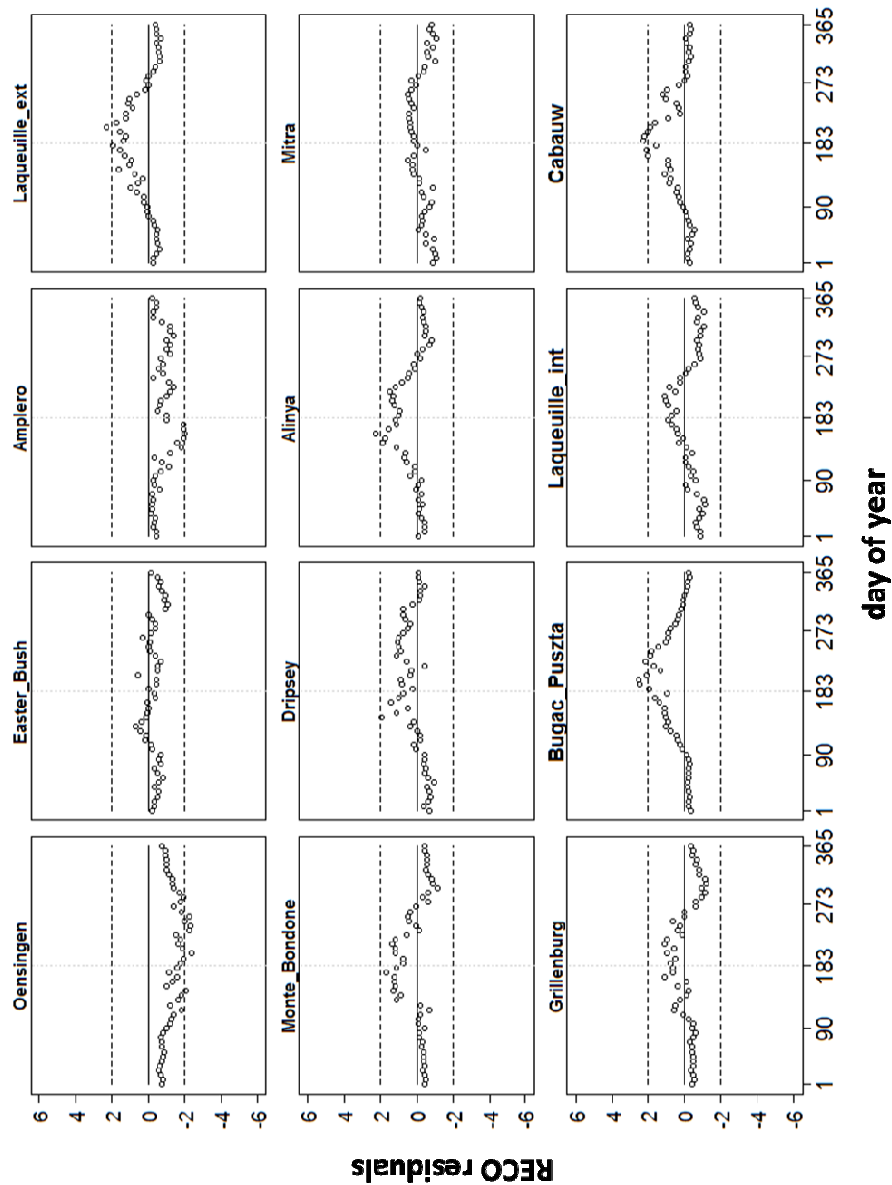


Fig. 7. Normalized residuals of RECO plotted versus day of year for each grassland site. Each point is the average of residuals for all years divided by the standard deviation. Horizontal lines represent the 95% confidence limits.

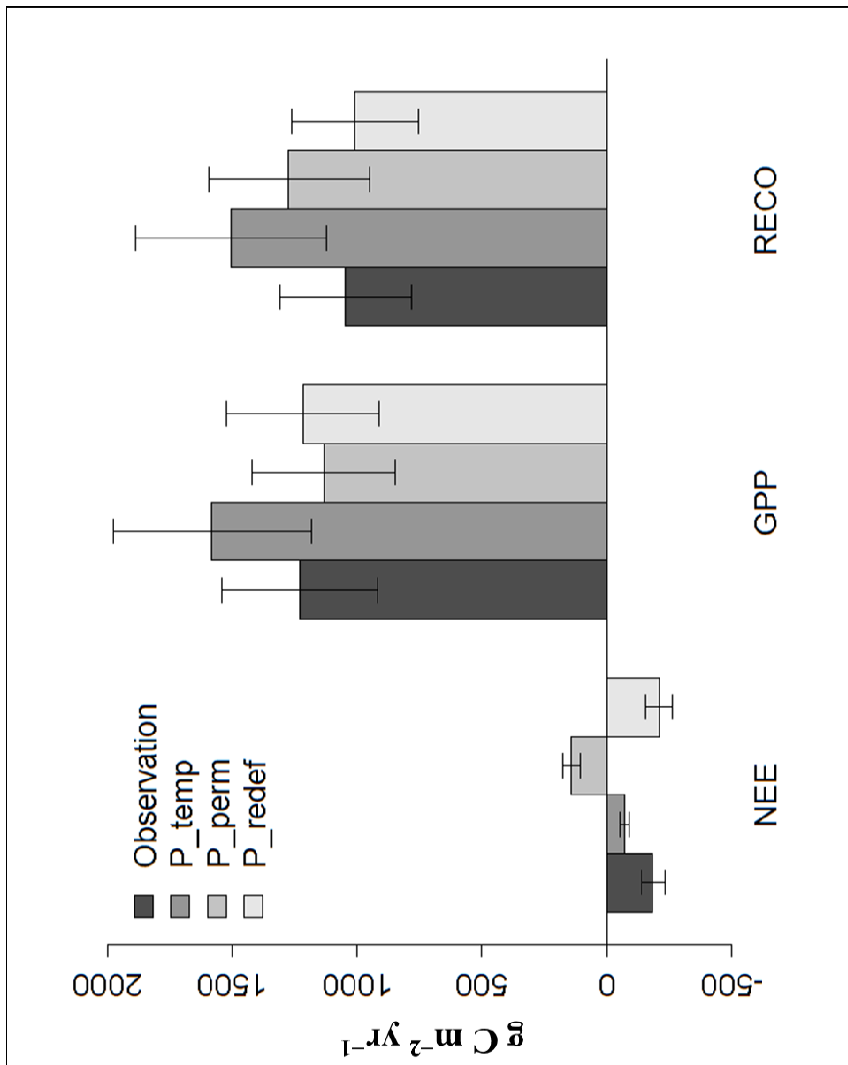


Fig. 8. Comparison of observed and simulated carbon fluxes (NEE, GPP, RECO; $\text{g C m}^{-2} \text{yr}^{-1}$) with different parameter values (default for Oensingen (P_temp) and Laqueuille (P_perm), and new parameter values (P_redef)). The values are averaged across all grassland sites.

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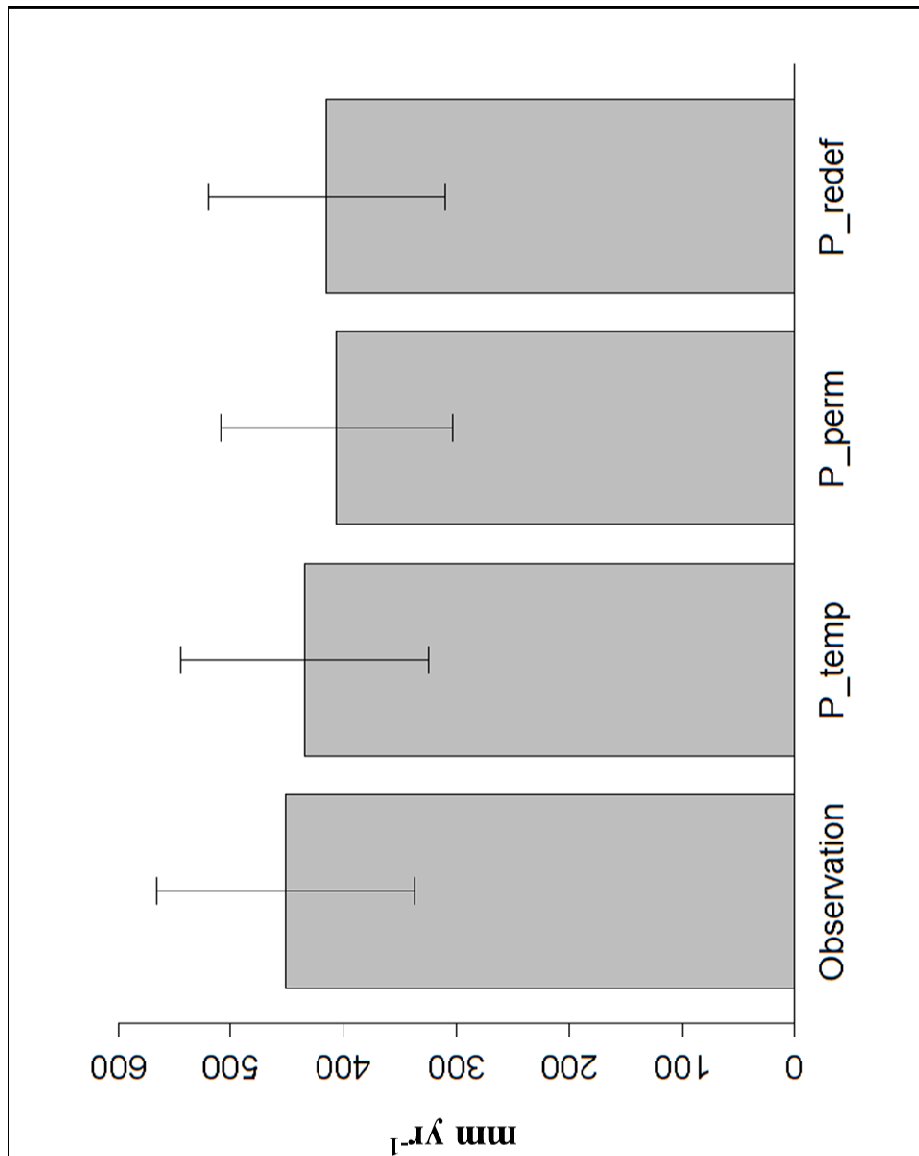


Fig. 9. Comparison of observed and simulated water fluxes (mm yr^{-1}) with different parameter values (default for Oensingen (P_temp) and Laqueuille (P_perm), and new parameter values (P_redef)). The values are averaged across all grassland sites.

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Appendix G: support figures

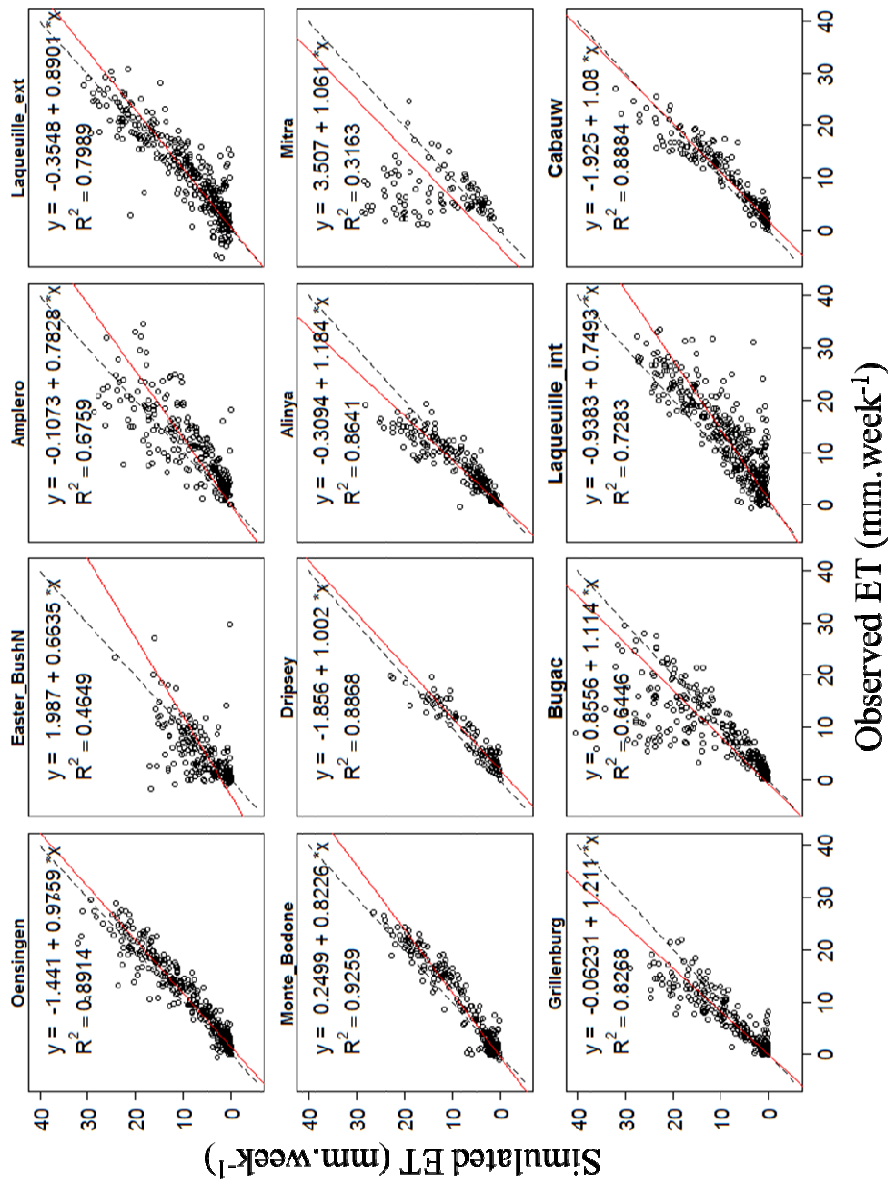


Fig. A1. Scatter plots of simulated versus measured ET weekly values.

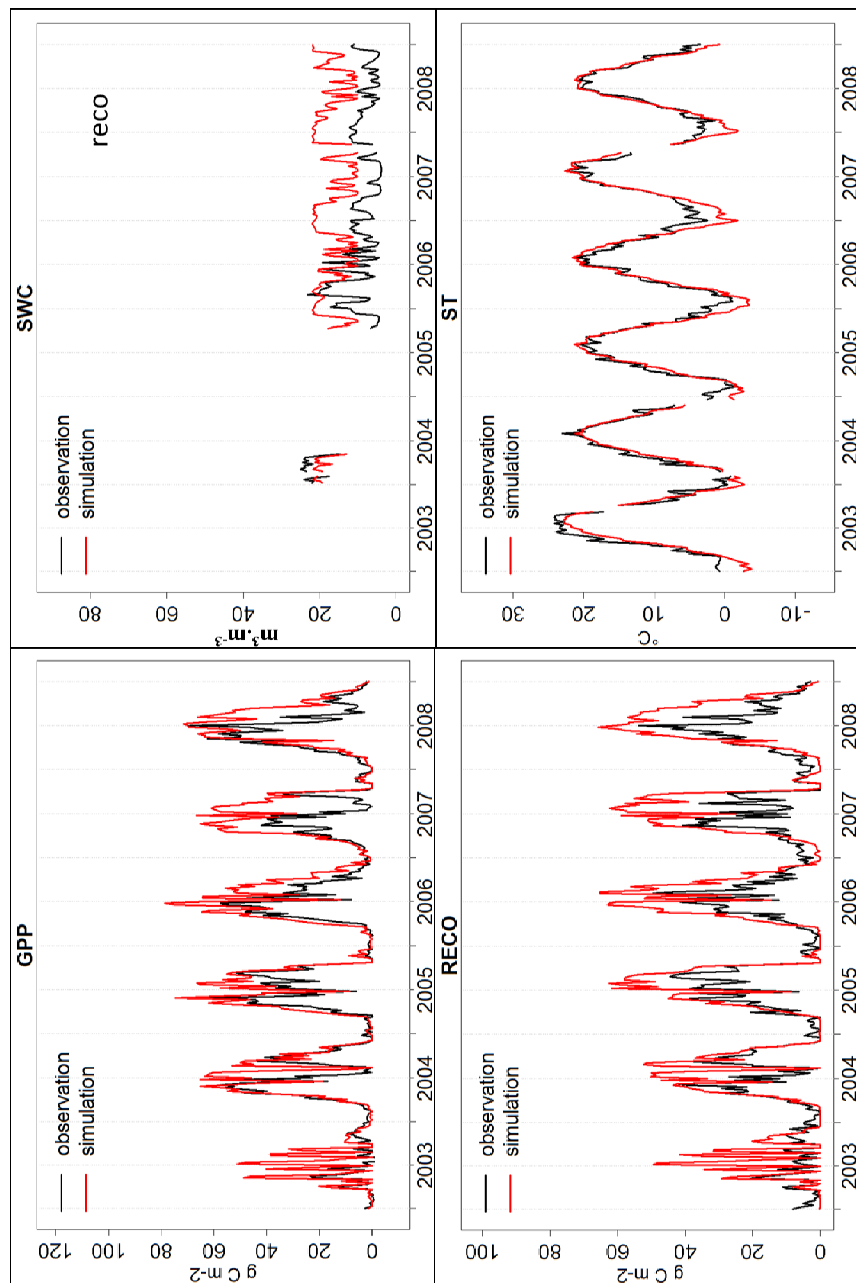
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Fig. A2. The variability of simulated GPP, RECO, soil temperature (ST) and soil water content (SWC) against the observed data for Bugac-Pusztá (Hungary) weekly values.

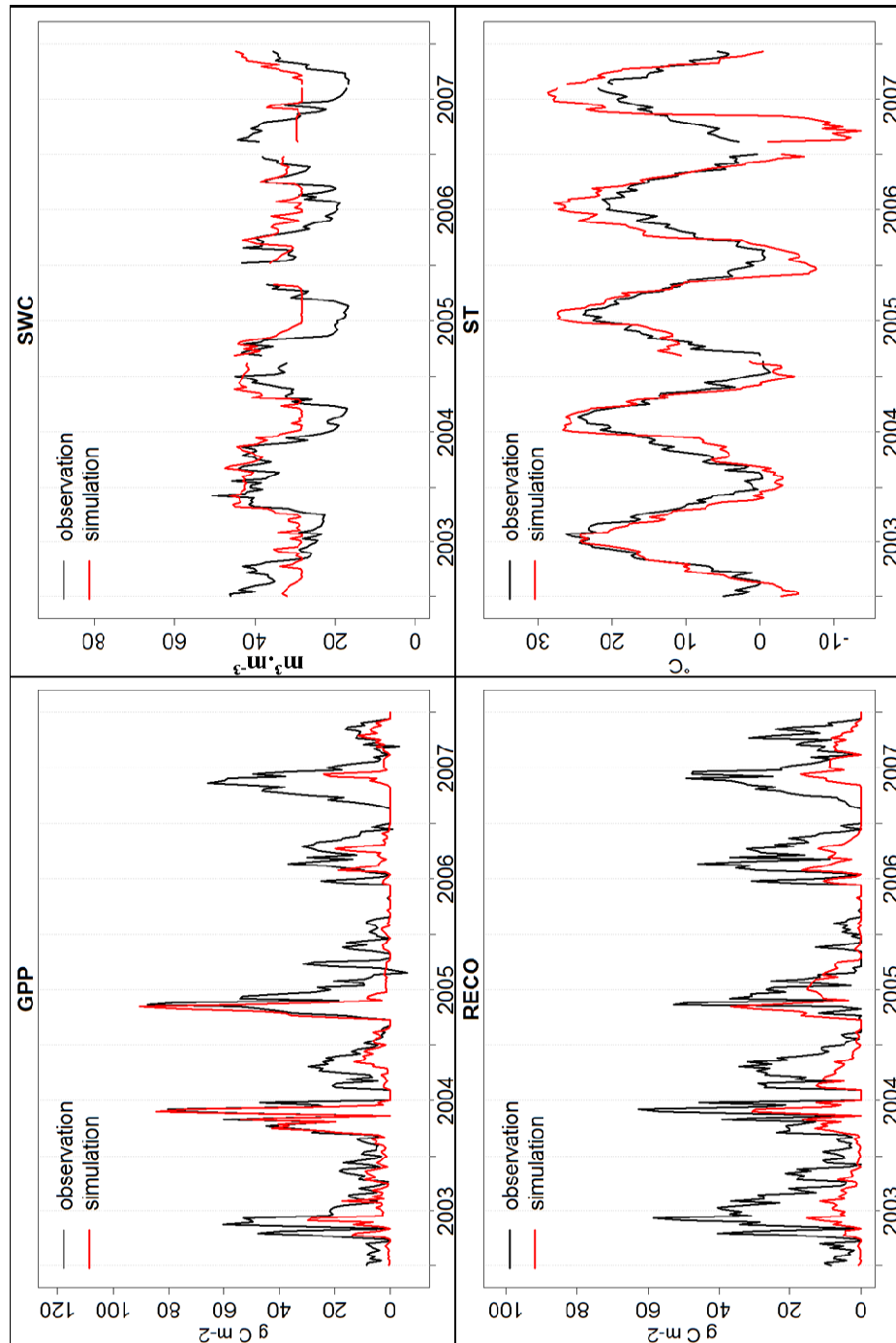
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Fig. A3. The variability of simulated GPP, RECO, soil temperature (ST) and soil water content (SWC) against the observed data for Amplero (Italy) weekly values.

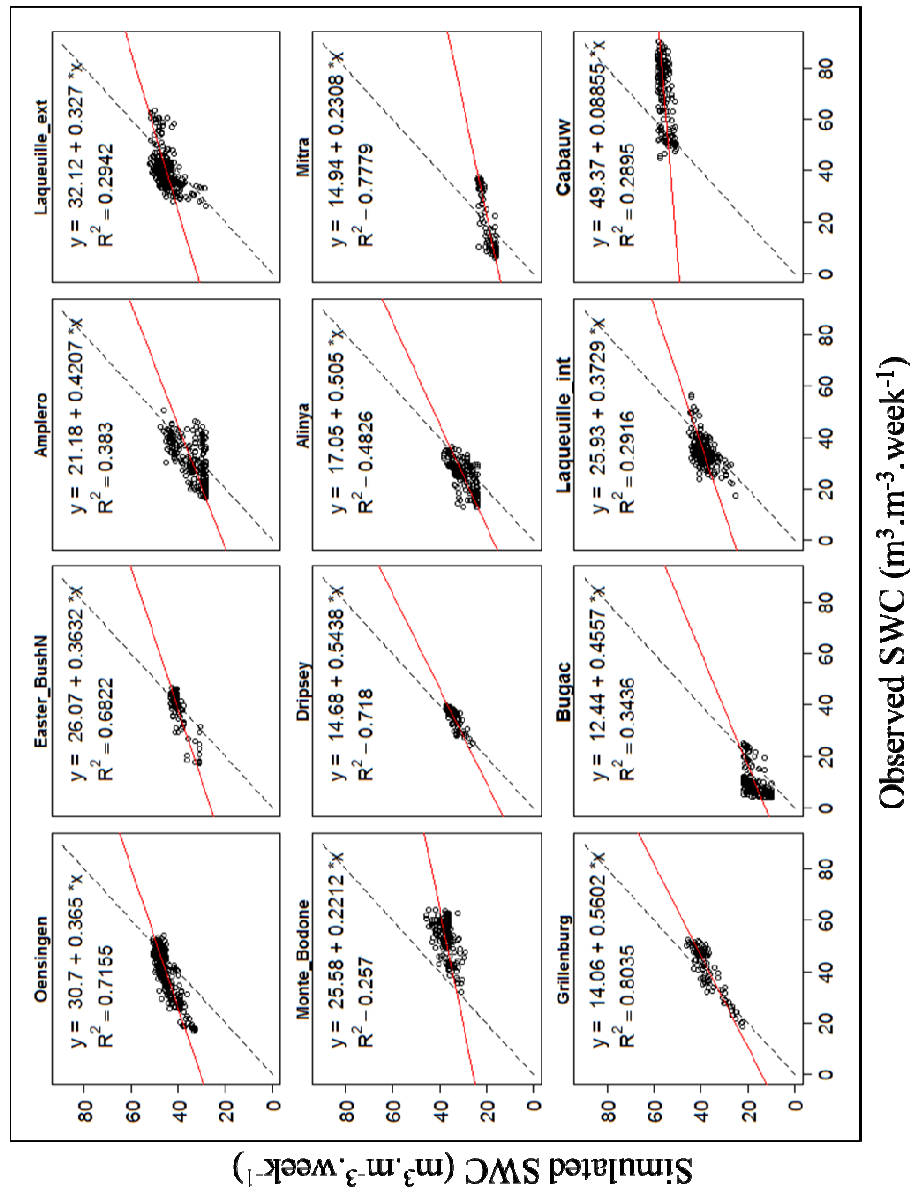


Fig. A.4. Scatter plots of simulated versus measured soil water content in the top 10 centimetres.

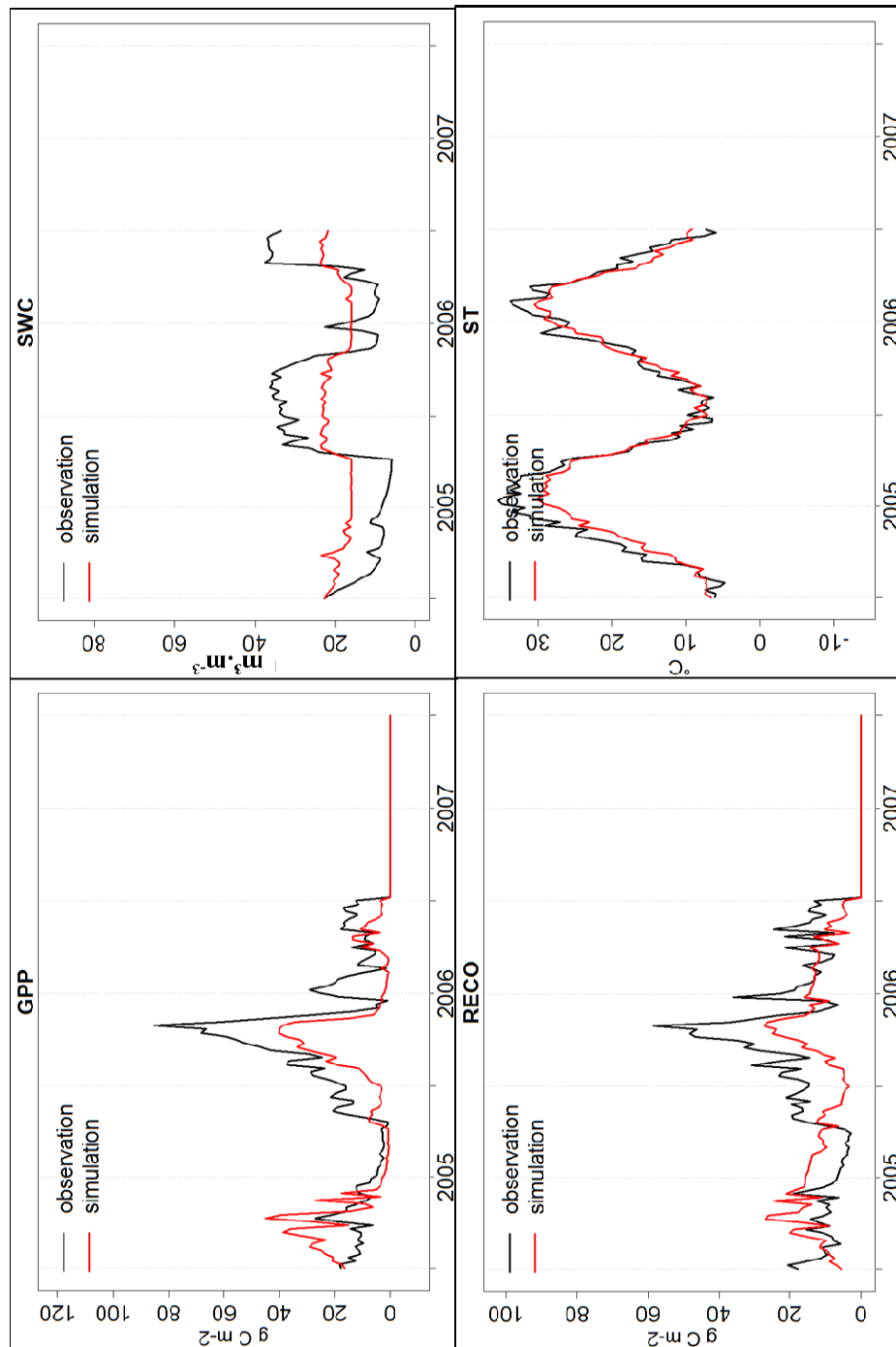
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Fig. A5. The variability of simulated GPP, RECO, soil temperature (ST) and soil water content (SWC) against the observed data for Mitra (Portugal) weekly values.

Comment citer ce document :

Ma, S., Lardy, R., Graux, A.-I., Ben Touhami, H., Klumpp, K., Martin, R., Bellocchi, G. (2015).
Regional-scale analysis of carbon and water cycles on managed grassland systems. *Environmental
Modelling and Software*, 72, 356-371. DOI : 10.1016/j.envsoft.2015.03.007