

1 Regional-scale analysis of carbon and water cycles on

2 managed grassland systems

Shaoxiu Ma¹, Romain Lardy^{2,3}, Anne-Isabelle Graux⁴, Haythem Ben Touhami¹, Katja Klumpp¹, Raphaël Martin¹, Gianni Bellocchi¹

¹⁰ *¹INRA, UR0874 Grassland Ecosystem Research, F-63039 Clermont-Ferrand, France*

¹¹ ² UMR 5505 IRIT, CNRS, University of Toulouse, France

12 ³ UMR 1248 AGIR, INRA-INPT, Castanet-Tolosan, France

¹³ ⁴ INRA – Agrocampus Ouest, UMR 1348 PEGASE, Domaine de la Prise, 35590 Rennes, France.

14 Saint-Gilles, France

1
2
3
4
5 **Abstract:**

6
7 Predicting regional and global carbon (C) and water dynamics on grasslands has
8
9 become of major interest, as grasslands are one of the most widespread vegetation
10
11 types worldwide, providing a number of ecosystem services (such as forage
12
13 production and C storage). The present study is a contribution to a regional-scale
14
15 analysis of the C and water cycles on managed grasslands. The mechanistic
16
17 biogeochemical model PaSim (Pasture Simulation model) was evaluated at 12
18
19 grassland sites in Europe. A new parameterization was obtained on a common set of
20
21 eco-physiological parameters, which represented an improvement of previous
22
23 parameterization schemes (essentially obtained via calibration at specific sites). We
24
25 found that C and water fluxes estimated with the parameter set are in good agreement
26
27 with observations. The model with the new parameters estimated that European
28
29 grassland are a sink of C with $213 \text{ g C m}^{-2} \text{ yr}^{-1}$, which is close to the observed net
30
31 ecosystem exchange (NEE) flux of the studied sites ($185 \text{ g C m}^{-2} \text{ yr}^{-1}$ on average).
32
33
34 The estimated yearly average gross primary productivity (GPP) and ecosystem
35
36 respiration (RECO) for all of the study sites are 1220 and $1006 \text{ g C m}^{-2} \text{ yr}^{-1}$,
37
38 respectively, in agreement with observed average GPP ($1230 \text{ g C m}^{-2} \text{ yr}^{-1}$) and RECO
39
40 ($1046 \text{ g C m}^{-2} \text{ yr}^{-1}$). For both variables aggregated on a weekly basis, the root mean
41
42 square error (RMSE) was $\sim 5\text{-}16 \text{ g C week}^{-1}$ across the study sites, while the goodness
43
44 of fit (R^2) was $\sim 0.4\text{-}0.9$. For evapotranspiration (ET), the average value of simulated
45
46 ET (415 mm yr^{-1}) for all sites and years is close to the average value of the observed
47
48 ET (451 mm yr^{-1}) by flux towers (on a weekly basis, RMSE $\sim 2\text{-}8 \text{ mm week}^{-1}$;
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63

1
2
3
4 37 $R^2=0.3-0.9$). However, further model development is needed to better represent soil
5 38 water dynamics under dry conditions and soil temperature in winter. A quantification
6
7 39 of the uncertainties introduced by spatially generalized parameter values in C and
8
9 40 water exchange estimates is also necessary. In addition, some uncertainties in the
10
11 41 input management data call for the need to improve the quality of the observational
12
13 42 system.

14
15 43

16
17 44

18
19 45

20
21 46 **Key word:**

22
23 47 Carbon flux, eddy flux measurements, model evaluation, Pasture Simulation model
24
25 48 (PaSim), water balance

26
27 49

1
2
3
4 50 **Software availability**
5 51 Name of Software: Pasture Simulation model (PaSim)
6 52 Developer: INRA, UR0874 initiative; contact: Raphaël Martin
7 53 Contact Address: INRA, UR0874 Grassland Ecosystem Research, 63039
8 54 Clermont-Ferrand, France
9 55 Telephone: +33-4-73624872
10 56 E-mail: raphael.martin@clermont.inra.fr
11 57 Availability: On request to the authors
12 58 Cost: free for no-profit use
13 59 Program language: Fortran
14 60
15
16
17
18
19 61
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63

1 2 3 4 5 **1. Introduction**

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

25
26 Grasslands are a widespread vegetation type worldwide, covering nearly one-fifth of
27 the world's land surface (24 million km²) (Sutcliffe et al., 2005) and playing a significant
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4
5 role in the global C cycle (Scurlock and Hall, 1998; Ciais et al., 2010). At global scale,
6 grasslands were estimated to be a net C sink of about 0.5 Pg C per year (Scurlock and
7 Hall, 1998), but with high spatial heterogeneity and considerable uncertainty on the
8 estimate of C exchange. Janssens et al. (2005) estimated that grasslands provide a C
9 sink of $66 \pm 90 \text{ g C m}^{-2} \text{ yr}^{-1}$ over Europe. From an extensive network of flux towers,
10 Schulze et al. (2009) inferred a net C sink: net biome production (NBP) in European
11 grasslands of $57 \pm 34 \text{ g C m}^{-2} \text{ yr}^{-1}$. However, grassland ecosystems are the most
12 uncertain components of the Europe-wide C balance in comparison to forests and
13 croplands because only few data and grassland-specific models are available (Ciais et
14 al., 2010). As a consequence, it is urgent to improve and evaluate grassland models
15 based on recently-available eddy flux data.

16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34 Over the last decades, grassland models were developed with different research foci.
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65 CENTURY model was developed to simulate soil C, N, P, and S dynamics on a
monthly time step (Parton, 1988), with an updated version (DayCent) working on a
daily basis (Parton et al., 2007). The Grassland Ecosystem Model (GEM) (Chen et al.,
1996) linked biochemical, biophysical and ecosystem processes in a hierarchical
approach to simulate C and N cycles, with focus on natural grasslands. The LINGRA
model (Schapendonk et al., 1998) has been extensively applied to simulate growth of
grasses, including perennial ryegrass (Rodriguez et al., 1999) and timothy (van Oijen
et al., 2005) under northern and western European conditions. The Hurley Pasture
Model (Thornley, 1998) describes the fluxes of C, N and water in a grazed
soil-pasture-atmosphere system. DairyMod was designed to simulate not only

1
2
3
4
5 106 biophysical, but also dairy management options (Johnson et al., 2008). Several
6 107 integrated or whole farm system models were also available to simulate the
7 108 biogeochemical processes and also include decision support system, such as Whole
8 109 Farm Model (Bright et al., 2000), GP-FARM (Ascough et al., 2007), Integrated Farm
9 110 System Model (<http://www.ars.usda.gov/Main/docs.htm?docid=8519>) and FASSET
11 111 (Chirinda et al., 2011). An overview of the state of the art and the developments
12 112 needed for process-based modelling of grazed agricultural systems were addressed by
13 113 Snow et al. (2014).

14 114 Recently, attempts have also been made to introduce management options into global
15 115 dynamic vegetation and crop models in order to extend functionalities for grasslands
16 116 on regional and global scales. Biome and global dynamic vegetation models such as
17 117 LPJmL (Bondeau et al., 2007), Biome-BGC (Hidy et al., 2012), ORCHIDEE (Krinner
18 118 et al., 2005) and CARAIB (Warnant et al., 1994) were improved with mowing and
19 119 grazing options. At the same time, widely used crop models, such as STICS (Brisson
20 120 et al., 2003; Ruget et al., 2009), EPIC (Williams et al., 1989), CropSyst (Stöckle et al.,
21 121 2003), DNDC (Rafique et al., 2011; Wang et al., 2012), DSSAT (Giraldo et al., 1999)
22 122 and the APSIM platform (Holzworth et al., 2014) have also been adapted to simulate
23 123 grasslands. These efforts have made great contributions to the overall development of
24 124 grassland models (yet with a different detail in representing processes). However,
25 125 model evaluation was limited in scope to specific goals (e.g. not all grassland models
26 126 simulate biogeochemical cycles). A detailed evaluation of model performance against
27 127 observational flux data from a variety of grassland sites is therefore desirable. In

1
2
3
4
5 128 particular, for a process-based model representing in detail the mechanisms driving
6
7 129 the functioning of grassland systems, evaluation is needed with extended datasets,
8
9 130 which include different grassland observational sites with a diversity of climatic,
10
11 131 management and soil conditions.

12
13 132 The process-based biogeochemical Pasture Simulation model (PaSim) is the focus of
14
15 133 this study. It was originally developed by Riedo et al. (1998), based on the Hurley
16
17 134 Pasture Model (Thornley, 1998), to simulate managed grasslands (clover-ryegrass
18
19 135 swards). PaSim includes both grazing and cutting management options and is able to
20
21 136 simulate a variety of temperate grassland ecosystems. Over the last decade, the model
22
23 137 has been continuously improved to simulate C, water and N cycles. New approaches
24
25 138 were integrated into the modelling structure to simulate, for instance, nitrous oxide
26
27 139 (N_2O) emissions from soils (Schmid et al., 2001a) and methane (CH_4) emissions from
28
29 140 animals (Vuichard et al., 2007a) as well as the performances (i.e. milk and meat
30
31 141 production) of grazing animals (Graux et al., 2011). The model has been used in the
32
33 142 climate-change impact studies (Graux et al., 2013; Vital et al., 2013), including an
34
35 143 assessment of the contribution of forage-based systems to the global warming (Graux
36
37 144 et al., 2012) with focus on France. However, PaSim has only been evaluated against a
38
39 145 few European grassland sites using short periods of observed C fluxes and biomass
40
41 146 production data, and based on limited parameterization (Vuichard et al., 2007a;
42
43 147 Calanca et al., 2007). A full documentation and an extended evaluation of the model
44
45 148 over a large number of sites are required.

46
47 149 A monitoring network consisting of a total of 12 grassland sites was established in
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63

1
2
3
4
5 150 2002 and eddy-covariance flux measurements were made on this network within the
6
7 European projects of the 5th, 6th and 7th framework programs, such as GREENGRASS
8
9 (Soussana et al., 2007b), CARBOMONT (Bahn et al., 2008; Wohlfahrt et al., 2008),
10
11 CarboEurope (Gilmanov et al., 2010) and CARBO-Extreme (Reichstein et al., 2013).
12
13 154 This dataset provides a good opportunity to evaluate grassland model performances
14
15 because these sites cover a variety of grassland types with contrasting management
16
17 practices and representing different climate conditions.
18
19 157 The present study assesses the ability of PaSim to reproduce C and water fluxes of a
20
21 number of European long-term eddy flux measurement sites. To do so, three sets of
22
23 eco-physiological vegetation parameters (i.e. from permanent grassland, sown
24
25 grassland, and an adjusted set, which is the calibrated parameter values based on flux
26
27 measurements data and their plausible ranges) were applied in order to test whether a
28
29 common set of vegetation parameters is appropriate to represent model outputs at
30
31 European scale (regardless of the possible physiological dissimilarities among
32
33 grasslands species in different places in Europe). Model calibration was not applied
34
35 separately to each observational site. This did not make it possible to explore the
36
37 spatial variability of model parameters. Testing such a scenario appeared beyond the
38
39 scope of this paper since it implied too strong a deviation from the initial hypothesis
40
41 of this regional study. Rather, we calibrated the model simultaneously on all datasets
42
43 to find parameter values that would be applicable at regional scale. Multi-site
44
45 calibration can be characterized by lower uncertainty than site-specific calibration,
46
47 because more data are involved in the calibration process (e.g. Minunno et al., 2014).
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

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

178

179 **2. Materials and Methods**

180

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

1
2
3
4
5 202 it is grazed for a long period of time in the year (200 days), with intensive utilization
6
7 203 of the sward and gain of N from returns by animals. At Easter Bush, the low impact of
8
9 204 grazing pressure (in number of animals and duration) is instead compatible with an
10
11 205 extensive system because the N fertilization treatment does not exceed the threshold
12
13 206 ($>200 \text{ kg N ha}^{-1}$) conventionally set for intensively managed grasslands (e.g. Bos et
14
15 207 al., 2005).

16
17
18
19
20 208 Monthly and yearly summaries for the average temperature and total precipitation
21
22 209 were obtained from the hourly weather data available for each site. The yearly
23
24 210 reference evapotranspiration (ET_0 , mm) was also calculated, using the
25
26 211 Penman–Monteith method, which uses an hourly time step (Allen, 2005). These
27
28 212 weather summaries were the basis for calculating two bioclimatic indicators.

29
30
31 213 The aridity pattern (Fig. 1, right) is characterized by semi-arid to humid conditions,
32
33 214 with the average value of De Martonne-Gottmann index (b) ranging from 10-20 at
34
35 215 Mitra (Portugal) and Bugac-Puszta (Hungary) to 45 at Dripsey (Ireland). The climate
36
37 216 of Mitra is typically warm and dry for a large part of the year, with hot summers.
38
39 217 Bugac-Puszta represents a continental climate, with hot summers, rain showers and
40
41 218 mildly cold winters. The site is characterized by annual water deficit, as well as the
42
43 219 Mediterranean upland site of Amplero (Central Italy). The other sites are mostly
44
45 220 humid, with values of the aridity index around 30-50.

46
47
48
49
50
51
52
53
54 221

55
56 222 **2.2 Flux measurements**

57
58
59 223 Each study site was equipped with an eddy covariance system to determine the net

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

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

244
245 **2.3 Model description**

1
2
3
4
5 246 The Pasture Simulation model (PaSim, version 5.3,
6
7 247 <https://www1.clermont.inra.fr/urep/modeles/pasim.htm>) simulates C and N cycling in
8
9 248 grassland ecosystems (mixed swards) at a sub-daily time step. The model has evolved
10
11 249 over time, starting as a simulator of dry matter production and associated flows of C,
12
13 250 N and water in productive pastures (Riedo et al., 1998). The biological N fixation by
14
15 251 clover is simulated by assuming that clover fraction in the sward is fixed for the
16
17 252 specific location (after Riedo et al., 1998). PaSim was later improved by Schmid et al.
18
19
20 253 (2001b) with respect to the production and diffusion of N₂O (Riedo et al., 2002) the
21
22 254 exchange of NH₃ with the atmosphere by Vuichard et al. (2007a, b), the animal
23
24 255 herbage selection and intake, and the effects of diet quality on the emissions of CH₄
25
26
27 256 from grazing animals. More recently, Graux et al. (2011) further improved
28
29 257 functionalities to estimate the forage production and dry matter intake taking into
30
31 258 account selective grazing between vegetation compartments and the effect of high
32
33 259 temperatures on animals, while also simulating ruminant performance and enteric
34
35 260 CH₄ emissions during grazing according to the energy content of the intake. The
36
37 261 livestock system considers change in body weight of the grazing livestock and
38
39 262 simulates the level of milk and meat production with heifers, dairy and suckler cows
40
41 263 during the grazing period.

42
43
44
45
46
47
48
49
50
51 264 The model consists of five interacting modules: microclimate, soil, vegetation,
52
53
54 265 herbivores and management. The soil biophysical module simulates soil temperature
55
56
57 266 and moisture profiles for different soil layers based on soil physical properties and
58
59 267 hourly weather inputs and simulated plant water use. The soil biogeochemical module,

1
2
3
4
5 268 adapted by monthly time-step CENTURY's organic decomposition approach (Parton,
6
7 269 1988), evenly distributes litter into the whole soil profile. The litter is segregated into
8
9 270 its structural and substrate components, respectively supplying the structural and
10
11 271 metabolic soil pools. In addition, the soil organic matter is further separated into three
12
13 272 compartments (active, slow and passive) according to different decomposition rates.
14
15 273 Soil pools are interlinked to represent C and N first-order kinetics. The N cycle
16
17 274 considers N inputs to the soil via atmospheric deposition, fertilizer addition, symbiotic
18
19 275 fixation by legumes and animal faeces and urine. The inorganic soil N is available for
20
21 276 root uptake and is lost through the processes (leaching, volatilization and
22
23 277 nitrification/denitrification) leading to N₂O and N2 emissions to the atmosphere. The
24
25 278 vegetation module estimates the assimilated C by photosynthesis and allocates it
26
27 279 dynamically to one root and three shoot compartments, each of which consisting of
28
29 280 four age classes. The transition from one age category to the next is done using
30
31 281 threshold time values to calculate the age of biomass in a compartment from the input
32
33 282 of younger material and the loss of older material. C losses from the system are
34
35 283 through animal milking, enteric CH₄ emissions and from animal returns, and
36
37 284 ecosystem respiration. Accumulated aboveground biomass is either cut or grazed, or
38
39 285 enters a pool after senescing. Herbivores are considered during the time they were at
40
41 286 pasture (not during indoor periods). Management includes organic and mineral N
42
43 287 fertilizations, mowing and grazing, setting by the user or optimized within the model
44
45 288 to achieve some objectives.
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65 289

290 **2.4 Parameterization and Simulation**

291

292 **2.4.1 Parameterization strategies**293 In previous studies (Calanca et al., 2007; Vuichard et al., 2007b), PaSim was
294 evaluated for a temporary grassland at Oensingen (Switzerland) and an upland
295 permanent grassland at Laqueuille (France) based on a set of 26 parameters (Table 3).296 We assumed that a common set of eco-physiological model parameters can be
297 established to simulate C₃ grasslands (including grasses, forbs and legumes) under
298 contrasting climate and management regimes in Europe, while site-specific climate
299 and management conditions provide supplementary factors driving the actual
300 production of grasslands. Based on the set of parameters given in Table 3 and
301 sensitivity analysis results (Ben Touhami et al., 2013), the following two steps were
302 carried out to explore the parameter space and identify a common set of
303 eco-physiological model parameters for PaSim. First, the model was run at all sites
304 with two sets of default parameter values: temporary sown grassland (P_temp) and
305 upland permanent grassland (P_perm). Second, manual calibration was carried out for
306 these parameters, which were identified as influential parameters by Ben Touhami et
307 al. (2013). The values of some of these parameters were modified within their
308 plausible ranges (as from the published literature, documented by Graux, 2011) to
309 ensure realistic representation of a variety of outputs. The calibration work was
310 performed at all study sites together through a trial-and-error process comparing the
311 model predictions with observational data. The solutions obtained constitute a

1
2
3
4
5 312 satisfactory performance for all output variables according to the metrics of Table 4.
6
7 313 Even though optimization methods are available (Trudinger et al., 2007; Wang et al.,
8
9 314 2009), the manual calibration is useful for modellers to get a reference parameter set
10
11 315 reflecting expert knowledge and simple adjustment strategies. It was proven that
12
13 316 optimization methods may be problematic in confronting the interaction between
14
15 317 parameters of complex models (Hollinger and Richardson, 2005; Richardson et al.,
16
17 318 2010). The model performance was evaluated for each site separately and with all
18
19 319 sites combined, by comparing the simulated C and water fluxes with data from eddy
20
21 320 flux towers.

22
23
24
25
26
27
28 321
29
30
31

322 **2.4.2 Model simulation and evaluation**

323 For each site, simulations were carried out with three sets of parameter values
324 described above for all available years in each site

325 PaSim was initialized via a spin-up process using the current weather input. In
326 particular, soil C pools were initialized to steady-state by running the model over 100
327 years by looping the available meteorology at each site following Lardy et al. (2011).

328 The results of the spin-up process matched the supplied soil C measurements with a
329 relative error of about 10% on average ($\pm \sim 2\%$ standard error).

330 The agreement of model outputs against the following five plant and soil variables
331 was examined, gross primary productivity (GPP, $\text{kg C m}^{-2} \text{ d}^{-1}$), ecosystem respiration
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
333 ($\text{m}^3 \text{ m}^{-3}$) and actual evapotranspiration (ET, mm d^{-1}). Ecosystem respiration (RECO)

1
2
3
4
5 334 plays an important role in estimating global C balances of terrestrial ecosystems, and
6
7 335 its knowledge is required to assess the GPP of such ecosystem (as a sum of NEE, and
8
9 336 RECO, equations in appendixes A, B, C and D). Soil water content (SWC) and soil
10
11 337 temperature (ST) were estimated for each of the six layers that make up the soil
12
13 338 profile in PaSim (equations in appendixes E and F).

14
15 339 Different performance indices and threshold criteria (Bennett et al., 2013) were used
16
17 340 to evaluate the model (Table 4). In particular, the goodness-of-fit R^2 (coefficient of
18
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
22
23 343 (ME), the index of agreement (IA) and the root mean square error (RMSE) were
24
25 344 derived to assess quantitative differences. The mean bias (MB) is a measure of the
26
27 345 overall tendency of the model to under- or over-estimate (the systematic error) the
28
29 346 observations. The performance of the model was assessed on daily, weekly and
30
31 347 monthly time scales.

32
33 348

34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64

349 **3. Results**

350 This section first describes the study sites. Then, the comparison between PaSim
351 results obtained with three sets of parameter values (two previously established and
352 one established in this study) and observed C and water fluxes is illustrated. The
353 model improvement gained with the new parameterization is presented. As well, the
354 impact of both site-specific characteristics and management options on model
355 performances is illustrated, followed by a detailed analysis of the model performances
356 with focus on C and water balances. Only exemplary results (selected output variables
357 and sites) are reported graphically and the main outcomes discussed hereafter, while
358 the full set of results is provided online supplementary material.

359

360 **3.1 The improvement of the model performance with the redefined parameter
361 values**

362 The adjusted parameters (denoted P_new) essentially reflect that previously used at
363 the permanent grassland site of Laqueuille (P_perm) (Table 3). This indicates that
364 Laqueuille site resembles the European grasslands used in this study, with the
365 exception of four parameters: light-saturated leaf photosynthetic rate for reproductive
366 stage, light-saturated leaf photosynthetic rate for vegetative stage, maximum specific
367 leaf area, and temperature dependence factor of the soil respiration. Even though a
368 formal sensitivity analysis was not undertaken in this study, these parameters had a
369 significant impact on model outputs in a previous study (Ben Touhami et al., 2013).
370 For three parameters, the new values lie between those in the previous studies. For the

1
2
3
4
5 371 parameter governing soil respiration, previous modelling studies supported a default
6
7 372 value equal to 2, which was substantially decreased (down to 0.7) to obtain simulated
8
9 373 respiration values closer to observations. Given its impact on the modelled RECO,
10
11 374 characterization of this parameter will require further studies.

12
13
14
15 375 The estimation of GPP and RECO was improved (Fig. 2) with the redefined common
16
17 376 set of eco-physiological parameters (Table 3). GPP was overestimated at all sites
18
19 377 using the P_temp parameter set with the exception of Oensingen (the site where that
20
21 378 parameter set was originally derived) and, to a lesser extent, of Amplero. Using
22
23 379 P_perm parameter set (permanent grassland), the bias of GPP was reduced at seven
24
25 380 out of 12 sites. Applying the redefined P_redif parameter set (Table 3), the bias of
26
27 381 GPP was further reduced for most of the sites except Oensingen, Bugac-Puszta and
28
29 382 Amplero (Fig. 2).

30
31 383 With both P_temp and P_perm parameter sets, RECO was overestimated for most of
32
33 384 the sites, with the exception of Oensingen and Amplero (Fig. 2). With P_perm, a
34
35 385 slight underestimation was also obtained at intensively-managed Laqueuille (Fig. 2).

36
37 386 When the redefined parameter set was used, the bias of RECO was reduced at all sites
38
39 387 but Oensingen and Amplero. Overall, the estimated ET has a good agreement with the
40
41 388 observed values with no real improvement with the redefined parameter values (Fig. 2
42
43 389 and Fig. A1).

44
45 390

46
47 391 **3.2 The site variability of model performances with the redefined parameter**
48
49 392 **values**

1
2
3
4
5 393 Model performance in predicting GPP, RECO and ET (data aggregated on a weekly
6 basis) is closely linked with site-specific conditions such as soil moisture (e.g. dry
7 sandy soils versus humid soils). The model simulated well GPP and RECO for nine
8 out of 12 sites. The exceptions were the sites of Amplero, Mitra and Bugac-Puszta
9 (Fig. 3, Fig. 4 and Table 5), which are characterized by drier conditions than the other
10 sites. The R^2 for the estimated versus observed GPP was greater than 0.8 for most of
11 the sites and was lower than 0.5 at Amplero only ($R^2=0.40$) (Fig. 3). Similar results
12 were found when other indices, such as the slope of the regression, IA, ME and
13 RMSE were taken into account (Table. 5). Compared with GPP estimations, similar
14 model performances were found for RECO across sites, but R^2 values for RECO were
15 relatively lower than those obtained when simulating GPP. For RECO, R^2 values were
16 generally greater than 0.7 for most of the sites, but lower than 0.5 at Amplero
17 ($R^2=0.39$) and Mitra ($R^2=0.46$) (Fig. 4). At Oensingen, the model underestimated
18 RECO during winter time and there were also periods (e.g. 2007) when summer
19 modelled RECO was below of that measured (Fig. 5). However, winter RECO
20 underestimation was common to most of the sites (online supplementary material).
21
22 409 The model performance was satisfactory for predicting ET at most of the sites.
23
24 410 Exceptions were dry sites such as Amplero, Bugac-Puszta and Mitra (Fig. A1).
25
26 411
27
28 412 **3.3 The impact of site characteristics and management practices**
29
30 413 Site characteristics and management practices were observed to have an important
31 impact on the model ability to estimate RECO (Fig. 6), but they were less important
32
33 414

1
2
3
4
5 415 when predicting GPP, NEE, ET, and soil temperature (data not shown). Concerning
6 management practices, the model tended to underestimate or overestimate RECO,
7 respectively for intensively and extensively managed grasslands (Fig. 6). The
8 occurrence of cutting or grazing had no significant impact on the model performance
9 in predicting RECO. The model tended to slightly underestimate RECO for
10 temporary-sown grasslands, while simulations of permanent grasslands were in good
11 agreement with measured data (Fig. 6). Concerning site-specific conditions, RECO
12 was underestimated for non-montane grasslands (<800 m a.s.l.) and overestimated for
13 mountain sites (Fig. 6).

14
15 424 An analysis of the normalized residuals (where each residual is the difference between the
16 predicted and observed values divided by the standard deviation) showed seasonal patterns, which
17 differed by site (Fig. 7). On average, the model slightly underestimated weekly-aggregated RECO
18 in winter in most sites, but significantly overestimated it in summer time on Laqueuille extensive,
19 Monte Bondone, Alinya, Bugac-Puszta, and Cabauw (Fig. 7). However, most of the residuals fall
20 within the upper limit of the 95% confidence interval.

21
22 430

23 431 **3.4 C and water balances**

24
25 432 The mean annual C fluxes (NEE, GPP and RECO) are meant as a synthesis and a
26 complement to the model performances of PaSim presented in this study. They
27 showed a good agreement with observations using the redefined parameter set (Fig. 8).
28
29 435 With these parameter values, the estimated NEE flux was on average $213 \text{ g C m}^{-2} \text{ yr}^{-1}$,
30 which indicates a sink of C approaching the average NEE flux observed at the studied
31
32

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

437 sites ($185 \text{ g C m}^{-2} \text{ yr}^{-1}$) (Fig. 8). The estimated yearly average values of GPP (1220 g
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
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
440 (Fig. 8). As a consequence, the model overestimated the C sink by 15%. This is
441 mainly due to RECO, which is underestimated while GPP is in good agreement with
442 observations. The average value of simulated ET (415 mm yr^{-1}) for all sites and years
443 was close to the average value of the observations (451 mm yr^{-1}), which corresponded
444 to an underestimation by 8% (Fig. 9).

445

446 **4. Discussion**

447

448 **4.1 Model performance over European grasslands**

449 By evaluating PaSim at a variety of European sites, an improvement of model
13 performances was obtained with using a common set of parameter values to estimate
14
15 C and water fluxes at weekly and yearly time scales (Fig. 2, Fig. 8 and Table 3). The
16 discrepancy between the observed and estimated GPP and RECO values was reduced
17 compared with previous studies making us of parameter values obtained at specific
18 conditions (Calanca et al., 2007; Ciais et al., 2010). For instance, Calanca et al. (2007)
19 overestimated GPP of about 50% at Laqueuille (France).

456

457 **4.2 The spatial variability of the model performance**

458 The agreement between the observed and estimated GPP on arid sites (Bugac-Puszta,
36
37 Amplero) is not as good as on other sites (Fig. 3). The mismatch between observed
38 and estimated GPP values on these dry sites can be partially attributed to the fact that
39 the model did not simulate soil water content fluctuations during summer time well
40 (see effect of drought conditions for Bugac-Puszta, Fig. 2A and Amplero, Italy, Fig
41 A3). Previous studies confirmed that extreme drought events may have a significant
42 effect on C and water cycles (Ciais et al., 2005; Hussain et al., 2011). With all the
43 slope coefficients less than 1, the range of the simulated soil water content was
44 smaller than the observed range, while the intercept was well above 0 (Fig. A4),
45 indicating that the model overestimated the soil water content during dry periods and

underestimated it the rest of time. As a consequence, the overestimated soil water content during drought periods could explain the slight overestimation of GPP (Fig. A2). In contrast, at Mitra (Portugal), the underestimated GPP can be partially attributed to the underestimated soil water content during the growing season (Fig. A5) as water is the limitation factor of plant growth in arid regions. Underestimation of GPP was also obtained at Amplero (Italy), but the incomplete information available for this site (Fig. A3) about starting and ending dates of grazing (constant dates were used) makes interpretation of results difficult.

Comparing with GPP, a similar model performance for RECO was found, but R^2 for RECO is relatively lower than GPP (Fig. 3). The lower R^2 for RECO on most of the sites is mainly due to the underestimated RECO during winter as, for instance, at Bugac-Puszta (Fig. 7, A2). On one hand the underestimated RECO during winter can be attributed to underestimation of soil temperature in the same period as soil respiration is sensitive to temperature. Soil respiration, one of the main components of RECO, depends on soil moisture, clay content, soil organic matter and C assimilation (Bahn et al., 2008; Balogh et al., 2011; Migliavacca et al., 2011) and these are also the drivers of PaSim. On another hand, the overestimated RECO at Bugac-Puszta is partially due to overestimated GPP as more C substrate is available. A third reason might be that the model overestimated soil moisture content (Fig. A2 and Fig. A5) since soil moisture is one of the most important limiting factors of soil respiration especially in arid and semi-arid regions (Balogh et al., 2011). At Amplero and Mitra, RECO underestimation follows GPP underestimation (Fig. A3 and Fig. A5). Indeed,

1
2
3
4
5 490 RECO is intimately related to C supply (Bahn et al., 2008; Migliavacca et al., 2011).
6
7 491
8
9
10 492 **4.3 Effect of site-specific conditions and management practices**
11
12 493 Management practices affect grassland production and greenhouse gas emissions
13
14 494 from grassland systems (Schmitt et al., 2010; Zeeman et al., 2010; Luo et al., 2012;
15
16 495 Peichl et al., 2012). In this study, PaSim underestimated RECO for
17
18 496 intensively-managed grasslands such as Oensingen and Amplero and overestimated it
19
20 497 for extensively-managed grasslands (Fig. 6, 7). It is known that intensive management
21
22 498 practices can introduce pronounced changes to soil physical structure, which in turn
23
24 499 impact the soil water transport processes and the soil heterotrophic respiration
25
26 500 (Moyano et al., 2012; Ball, 2013). It is the case for the present study as PaSim did not
27
28 501 simulate adequately soil water fluctuations (Fig. 5, Fig. A2 and Fig. A3). At
29
30 502 Oensingen (Switzerland), the model did not represent well the soil temperature (Fig. 5.
31
32 503 This can be mainly attributed to the disturbance of management, which changed the
33
34 504 soil structure when converting cropland into grassland at Oensingen in 2001,
35
36 505 considering that tillage changes soil physical structure and, in turn, water and energy
37
38 506 transport processes (Acharya et al., 2012). The human management could also modify
39
40 507 microbial component and diversity (Cantarel et al., 2012), which significantly impacts
41
42 508 on the soil respiration (Allison et al., 2010; Wieder et al., 2013). Moreover, the
43
44 509 possibility to introduce more uncertainties is high due to imprecise input management
45
46 510 information such as grazing, cutting, and fertilization rate and timing.
47
48
49
50
51
52
53
54
55
56
57
58
59
511
60
61
62
63
64

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.

529

1
2
3
4 530 **5. Conclusions and perspectives**
5 531
6
7 532 **5.1 Summary of findings of the regional-scale analysis**
8
9
10 533 A regional-scale analysis of C and water cycles was performed on a variety of
11
12 534 European grassland sites using a process-based model (PaSim) with a single set of
13
14 535 eco-physiological parameters. It was shown that: 1) variables of C and water cycles
15
16 536 (mainly GPP, RECO and ET) can be reasonably simulated by PaSim at European
17
18 scale using a common set of parameter values; 2) better model performances are
19
20 537 obtained at more humid sites; 3) RECO tends to be underestimated in
21
22 538 intensively-managed grasslands and overestimated at sites when extensive
23
24 539 management practices are adopted.
25
26
27
28
29
30 541 The parameterization for mechanistic simulation of grasslands (with biogeochemical
31
32 542 capabilities) is a general way to facing regional studies. We have pursued in this study
33
34 543 the question of to what extent calibration can improve the parameterization of a
35
36 544 complex grassland model for regional-scale simulations in Europe. Acting upon the
37
38 545 most influential parameters of PaSim, we have derived a set of parameter values of
39
40 546 general validity in Europe. Even if for specific purposes process-based models need to
41
42 547 be parameterized on a site-specific basis, our multi-dataset procedure demonstrates
43
44 548 that it is possible to find global estimates for those parameters that encompass a wide
45
46 549 range of conditions. The accurate estimation of C and water fluxes relies on the
47
48 550 mechanistic representation of key ecosystem processes, with parameters that can be
49
50 551 related to physical quantities, thus the perspective of using a regionally calibrated
51
52 552 model regulating energy and matter exchanges is more interesting than applying
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4
5 553 statistical models (Laniak et al., 2013). In addition, statistical model estimations may
6 involve significant levels of collinearity among predictor variables such as
7 temperature and precipitation. They also rely on the assumption of stationarity (e.g.
8 assuming that past relationships will hold in the future, even if factors such as climate
9 and management evolve) and are subject to problems of low signal-to-noise ratios in
10 yield or weather records in many locations (Lobell and Burke, 2010). The main
11 finding is that the satisfactory performance obtained over contrasting climate
12 conditions and management options justify the use of PaSim in regional studies on C
13 and water fluxes in Europe. In C-water flux studies, this is especially relevant when
14 daily-resolution outputs are mainly analysed in temporally-aggregated form - that is,
15 the interest is in weekly, monthly or higher timeframes (e.g. Wallach and Thorburn,
16 2014).
17
18 565
19
20 566 **5.2 Future work on grassland modelling**
21
22 567 Our results indicate further model development is needed to address specific needs
23 and this is critical under the pressure of a changing climate and related extreme
24 weather events, potentially altering the C cycles at different scales (Field et al., 2011).
25
26 570 A first issue is that heat waves and dry spells have (favouring conditions of aridity) a
27 direct effect on CO₂ fluxes because warmer temperatures and soil moisture shortage
28 affect both photosynthesis and respiration. Moreover, as changes in seasonal water
29 availability have pronounced effects on individual species, a prominent role is
30 suggested for species interactions in ecosystem responses to climate changes (Suttle et
31
32 574
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4
5 575 al., 2007). Adaptation and functional biodiversity would dampen down the effect of
6 climate extremes on the C cycle, but the bases for biological adaptation and the role of
7 biodiversity are still unclear (Reichstein et al., 2013b). The use of functional traits of
8 plants, for which plant species are classified into functional types based on vegetative
9 and reproductive traits, proposed by Cruz et al. (2002) can be a promising avenue for
10 future research (Duru et al., 2013). But the level of detail of this study is too low to
11 draw conclusions about the relationship between model parameters and phenotypic
12 traits.
13
14

15 583 To obtain reliable estimates of the sign (source or sink) and magnitude of C-cycle
16 feedbacks, future research should provide a mechanistic basis for inferring effects of
17 extreme meteorological events on the C cycle. This would also help capturing the
18 impacts of drought events on grasslands because drought avoidance of grassland
19 plants mainly depends on rooting depth and soil water reserves. Concepts by Baker et
20 al. (2008) and Sheikh et al. (2009), which consider root access to the stored water in
21 the deep soil water during the drought season, could be integrated into PaSim.
22
23

24 590 The soil temperature module is another area of the model to be improved to better
25 predict soil temperature over winter. This is especially critical for high-altitude
26 grasslands, where vegetative growth restarts at snowmelt. This would also improve
27 the estimation of soil respiration, for which soil temperature is a key driver.
28
29

30 594 Moreover, we acknowledge that the dynamics of aboveground biomass accumulation
31 (either cut for yield production or grazed by animals) were not considered in the study
32 design. Biomass data are mostly discontinuously measured and rather large
33
34

1
2
3
4
5 597 uncertainties on biomass measurements (mainly owing to spatial heterogeneity) may
6 598 hinder model evaluation (Vuichard, 2007b). A better model performance (yet
7 599 integrating biomass measurements) could be attained by optimizing model parameters
8 600 through model-data fusion methods such as Bayesian calibration (van Oijen et al.,
9 601 2011). Studies of this type are underway on PaSim (Ben Touhami et al., 2012a, b)
10 602 with attention given to the interaction among parameters.
11
12 603 The improvements of PaSim also include the development of scalable solutions with
13 604 fundamental plant science research (a broad range of basic impact processes, open to
14 605 a wide range of plant types) and transition of software engineering technology into
15 606 modelling practice (Martin et al., 2011; Lardy et al., 2014), while addressing
16 607 re-usability issues and inter-linking of model components (Donatelli et al., 2012).
17
18 608 For managed grasslands, complete management information is often unavailable for
19 609 regional studies. High-quality grassland management data are needed to better
20 610 understand their effects on the soil physical structure and C storage (Flechard et al.,
21 611 2007; Schmitt et al., 2010; Chang et al., 2013).
22
23 612 The model improvement actions are ongoing under the guidance and conditions laid
24 613 down by a number of international projects and initiatives (e.g. AgMIP,
25 614 <http://www.agmip.org>), and will be expanded by the EU-FP7 project
26 615 MODEXTREME (<http://modextreme.org>).
27
28 616
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63

617 **Acknowledgments**

618 The results of this research were obtained within an international research project
619 named “FACCE MACSUR – Modelling European Agriculture with Climate Change
620 for Food Security, a FACCE JPI knowledge hub”. The data used were obtained with
621 the support of EU projects CarboEurope–IP (FP6 GOCE-CT-2003-505572) and
622 CARBO-Extreme (FP7-ENV-2008-1-226701). We thank Partner Institutions for
623 providing grassland data. We also acknowledge technical support from the European
624 Fluxes Database Cluster (<http://www.europe-fluxdata.eu>). Several reviewers and the
625 editors helped considerably in improving the manuscript.

626

1
2
3
4 **APPENDICES**
5
6

7 **Appendix A - Primary production**

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

15
$$NPP = GPP - R_{pl,tot} \quad (1)$$

16
17

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

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

30
$$NEE = RECO - GPP \quad (2)$$

31
32

33 with positive values indicating the system is a source of C losses, and negative values
34 indicating that the system sequesters C from the atmosphere.
35
36

37 **Appendix B - Total plant respiration**
38
39

40 A single process of respiration is associated with growth (Thornley, 1998). A
41 component of this respiratory flux is deemed to be maintenance respiration (generally
42 associated with the re-synthesis of degrading tissue), while also taking into account
43 the energy required for mineral uptake. The dependence of respiratory components on
44 C substrate supply is represented by separating C substrate from structure and
45 coupling the respiration flux to photosynthesis. This allows simulating variation in the
46 fractions of total plant respiration associated with different processes during plant
47 development.
48
49

50 Total plant respiration, $R_{pl,tot}$ (kg C m⁻² d⁻¹), is given by:
51
52

1
2
3
4 657 $R_{pl,tot} = R_{m,rt} + R_{m,sh} + R_{G,rt} + R_{G,sh} + R_N$ (3)
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

$$R_{pl,tot} = R_{m,rt} + R_{m,sh} + R_{G,rt} + R_{G,sh} + R_N \quad (3)$$

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

662

663 *Growth respiration rates*

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

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

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

668 The term $I/Y_{G,pl}$ is an efficiency measure representing the kg of C required to create 1
669 kg of structural C, $Y_{G,pl}$ being the photosynthetically-assimilated C initially allocated
670 to substrate C reserves and then used for growth and maintenance of tissues. For the
671 fraction required for growth, growth rates ($\text{kg C m}^{-2} \text{ d}^{-1}$) are calculated for
672 aboveground ($I_{C,G,sh}$) and belowground ($I_{C,G,rt}$) biomass, based on allocation values
673 occurring during the vegetative stage ($I_{C,G,sh,veg}$ and $I_{C,G,rt,veg}$, $\text{kg C m}^{-2} \text{ d}^{-1}$), modified in
674 favour of aboveground biomass during the reproductive stage. The coefficient $Y_{G,pl}$ is
675 set equal to 0.75 to represent plant growth efficiency ($\text{kg C} (\text{kg C})^{-1}$).

676 C allocation fluxes into roots ($I_{C,G,rt}$) and aboveground ($I_{C,G,sh}$) plant parts are as
677 follows:

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

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

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

681 The terms $I_{C,G,sh,veg}$ and $I_{C,G,rt,veg}$ are calculated on a constant growth rate at 20 °C ($I_{C,G,20}$,
682 usually set equal to $150 \text{ kg}^2 (\text{kg C})^{-1} (\text{kg N})^{-1}$), applied to the cumulative structural
683 biomass of roots and shoots (W_{sh} , W_{rt} , kg DM m^{-2}) and modulated by factors of

1
2
3
4 684 temperature ($f_{T,G}$) and substrate C and N concentrations in shoots and roots (C_{sh} , C_{rt} ,
5 kg C (kg DM) $^{-1}$; N_{sh} , N_{rt} , kg N (kg DM) $^{-1}$), as follows:

6 686 $I_{C,G_{sh,veg}} = I_{C,G20} \cdot f_{T,G} \cdot C_{sh} \cdot N_{sh} \cdot W_{sh}$ (8)

7 687 $I_{C,G_{rt,veg}} = I_{C,G20} \cdot f_{T,G} \cdot C_{rt} \cdot N_{rt} \cdot W_{rt}$ (9)

8 688

9 689 *Maintenance respiration rates*

10 690 The respiration fluxes to maintain metabolic processes (those that do not result in a
11 net increase in plant dry matter) of roots ($R_{m,rt}$) and shoots ($R_{m,sh}$) are a function of
12 substrate C concentration (C , kg C kg DM $^{-1}$), structural biomass ($W_{sh} \cdot f_{C,sh}$, $W_{rt} \cdot f_{C,rt}$)
13 and a temperature-dependent stress factor (Table 3):

14 694 $R_{m,sh} = \frac{C}{C+K_{C,mai}} \cdot R_{m,sh,temp}$ (10)

15 695 $R_{m,rt} = \frac{C}{C+K_{C,mai}} \cdot R_{m,rt,temp}$ (11)

16 696 where $K_{C,mai}$ is a maintenance respiration parameter, set equal to 0.03 kg substrate C
17 (kg structural DM) $^{-1}$ d $^{-1}$. The terms $R_{m,sh,temp}$ and $R_{m,rt,temp}$ are temporary shoot and root
18 maintenance respiration, respectively, as follows:

19 699 $R_{m,sh,temp} = f_{T,sh} \cdot \sum_{j=1}^4 k_{mai,j,20} \cdot W_{sh,j} \cdot f_{C,sh}$ (12)

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

21 701 These maintenance respiration factors are transient in nature since they apply to
22 temporary values. Both shoot and root biomasses are indeed divided into four state
23 variables representing four age categories ($j=1, \dots, 4$), for which the following values
24 are given for the maintenance respiration parameter at 20 °C, $k_{mai,j,20}$ (kg C
25 kg $^{-1}$ structural C d $^{-1}$): 0.020 ($j=1$), 0.020 ($j=2$), 0.015 ($j=3$), 0.010 ($j=4$).

26 706 The terms $f_{C,sh}$ and $f_{C,rt}$ (kg C kg $^{-1}$ DM) are fractional C content in shoot and root
27 structural dry matter, respectively (reference values are 0.50 and 0.39, respectively).

28 708

29 709 *N uptake respiration rate*

30 710 The respiration flux associated with N uptake (R_N , kg C m $^{-2}$ d $^{-1}$) is:

31 711 $R_N = k_N \cdot IN_{soil,rt}$ (14)

32 712 where $IN_{soil,rt}$ (kg N m $^{-2}$) is the mineral N (NO $_3^-$ -N and NH $_4^+$ -N) uptake by the sward,

1
2
3
4 713 and k_N is the respiratory cost of N uptake (the reference value being 0.45 kg C kg⁻¹ N).
5
6 714

7 715 **Appendix C – Heterotrophic soil respiration**

8 716 Apart the biological activity of roots and associated micro-organisms, the flux of CO₂
9 717 from the soil to the atmosphere is the result of the production of CO₂ from the activity
10 718 of heterotrophic bacteria and fungi living on litter and in the root-free soil (after
11 719 Parton, 1988). The soil organic carbon (SOC) pool is divided into five pools with
12 720 different turnover times ranging from 0.5 to 1500 years. An additional component is
13 721 given by the amount of C released as exudates (*exu*) from roots into the soil, estimated
14 722 as a fraction of plant substrate C. The litter in decomposition over the total soil depth
15 723 splits into its structural and substrate components, supplying the structural (*str*) and
16 724 metabolic (*met*) soil pools respectively. Other three compartments with different
17 725 decomposition rates include active (*act*), slow (*slo*) and passive (*pas*) pools of SOC,
18 726 consisting of the microbial biomass, refractory components of litter and highly
19 727 humified organic compounds respectively.

20 728 Total heterotrophic soil respiration, R_{SOC} (kg C m⁻² d⁻¹), is given by:

21 729
$$R_{SOC} = R_{str} + R_{met} + R_{exu} + R_{act} + R_{slo} + R_{pas} \quad (15)$$

22 730

23 731 *Soil respiration from structural organic matter*

24 732 The respiration flux associated with structural SOC (R_{str} , kg C m⁻²d⁻¹) is:

25 733
$$R_{str} = (1 - f_{lig,str}) \cdot f_{r,str} \cdot f_{C,str} + f_{lig,str} \cdot f_{r,str,lig} \cdot f_{C,str} \quad (16)$$

26 734 The microbial respiration parameter for the decomposition of the structural pool, $f_{r,str}$,
27 735 and of lignin, $f_{r,str,lig}$, are set equal to 0.55 and 0.3, respectively. The term $f_{lig,str}$ is the
28 736 fraction of lignin in structural soil organic matter. The fraction of C in the structural
29 737 plant residue, $f_{C,str}$, is as follows:

30 738
$$f_{C,str} = k_{str} \cdot W_{C,str} \quad (17)$$

31 739 where k_{str} (kg C m⁻² d⁻¹) is the decomposition rate for the structural pool and $W_{C,str}$ (kg
32 740 C m⁻²) is the C content in structural fraction of plant residue (depending on
33 741 temperature, lignin, texture and water content).

34 742

743 *Soil respiration from metabolic organic matter*

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

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

746 The microbial respiration parameter for the decomposition of the metabolic pool, $f_{r,met}$,

747 is set equal to 0.55. The fraction of C in metabolic pool, $f_{C,met}$ (kg C m⁻²), is calculated
 748 assuming linear kinetics.

749

750 *Soil respiration from exudates*

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

$$752 \quad R_{exy} \equiv f_{x exy} : f_{C exy} \quad (19)$$

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
 754 for root exudation.

755

756 Soil respiration from active organic matter

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

$$758 \quad R_{\text{act}} \equiv f_{\text{react}} \cdot f_{C,\text{act}} \quad (20)$$

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

$$760 - f_{\text{rest}} = 0.85 - 0.68 \cdot (f_{\text{rest},\text{st}} + f_{\text{rest},\text{st}}) \quad (21)$$

where f_{clay} and f_{silt} are fractions of clay and silt, respectively.

762

763 Soil respiration from slow organic matter

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

$$765 \quad R_{\alpha\beta} = f_{\alpha\beta} + f_{\beta\alpha} \quad (22)$$

766 The microbial respiration parameter for the decomposition of the slow pool, $f_{r,slo}$, is set
 767 equal to 0.55. The fraction of C in slow fraction, f_s (kg C m^{-2}), is calculated as

360

774 W_{pool} (kg C m^{-2}) is the C content in slow pool (depending on temperature, lignin

772 texture and water content). The term $k_{\text{slow}} \cdot (d_0^{-1})$ is the turnover rate for slow C pool at

1
2
3
4 773 20 °C, equal to 0.00027. The terms $k_{dec,t}$ and $k_{dec,\theta}$ are factor activities of soil organic
5 matter for temperature and water content, respectively.
6
7 775
8
9 776 *Soil respiration from passive organic matter*
10
11 777 The respiration flux associated with active SOC (R_{pas} , kg C m⁻²d⁻¹) is:
12
13 778 $R_{pas} = f_{r,pas} \cdot f_{C,pas}$ (25)
14
15 779 The microbial respiration parameter for the decomposition of the passive pool, $f_{r,pas}$, is
16 set equal to 0.55. The fraction of C in passive pool, $f_{C,pas}$ (kg C m⁻²), is calculated
17 assuming linear kinetics.
18
19 780
20
21 781
22
23 782
24 783 **Appendix D - Respiration from grazing animals**
25
26 784 Half of the C in plant material consumed by grazing animals ($I_{C,veg \rightarrow ani}$, kg C m⁻² d⁻¹)
27
28 785 is assumed to be respired (R_{ani} , kg C m⁻²d⁻¹):
29
30 786 $R_{ani} = 0.5 \cdot I_{C,veg \rightarrow ani}$ (26)
31
32 787 The amount of ingested C is estimated as follows:
33
34 788 $I_{C,veg \rightarrow ani} = (f_{C,sh} + C) \cdot \frac{W_{sh}}{W_{sh,tot}} \cdot I_{veg \rightarrow ani}$ (27)
35
36 789 where ($I_{veg \rightarrow ani}$, kg DM m⁻² d⁻¹) is the amount of ingested dry matter, which increases
37 with the aboveground plant biomass ($W_{sh,tot}$, kg DM m⁻²) available for the animals
38 790 (W_{sh} , kg DM m⁻², is the cumulative structural aboveground biomass), limited by the
39 791 maximum ingestion capacity the animal is able to maintain (I_{max} , whose reference
40 792 value is 16 kg DM d⁻¹ animal⁻¹).
41
42 793
43
44 794
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64

795 Appendix E - Soil temperature

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

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

800 Where $T_s(h)$ (K) is the soil temperature at the midpoint of the i^{th} layer in the present
 801 time step, $\dot{T}_s(h)$ (K) is soil temperature in the same layer but one time step in the past,
 802 and $T_s^*(h)$ (K) is temperature in the i^{th} layer at some time between the two time steps.

804 Appendix F - Soil water balance

The water content in the different soil layers determines photosynthesis and stomatal conductance, soil evaporation, and rates of soil biological processes, and is used to calculate soil temperature in the different layers, which influences belowground plant processes, soil heat flux, and soil biological processes. Values of the soil matrix potential in soil layer h , $\psi(h)$ (m), is related to the water content in the same layer, $\theta_s(h)$ ($\text{m}^3 \text{ m}^{-3}$) by the soil moisture characteristic (Campbell, 1985):

$$811 \quad \theta_s(h) = \theta_{s,sat}(h) \cdot \left[\frac{\psi_e(h)}{\psi(h)} \right]^{\frac{1}{b(h)}} \quad (29)$$

812 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
 813 air entry water potential (m) in soil layer h , $b(h)$ is a physical parameter for soil layer
 814 h .

815 **References**

- 816 Acharya, B.S., Rasmussen, J., Eriksen, J., 2012. Grassland carbon sequestration and emissions
 817 following cultivation in a mixed crop rotation. *Agriculture, Ecosystems & Environment*
 818 153, 33–39. doi:10.1016/j.agee.2012.03.001
- 819 Addiscott, T.M., Whitmore, A.P., 1987. Computer simulation of changes in soil mineral nitrogen
 820 and crop nitrogen during autumn, winter and spring. *The Journal of Agricultural Science*
 821 109, 141-157. doi:10.1017/S0021859600081089
- 822 Aires, L.M.I., Pio, C.A., Pereira, J.S., 2008. Carbon dioxide exchange above a Mediterranean C3/C4
 823 grassland during two climatologically contrasting years. *Global Change Biology* 14,
 824 539–555. doi:10.1111/j.1365-2486.2007.01507.x
- 825 Allen, R.G., Walter, I.A., Elliot, R.L., Howell, T.A., Itenfisu, D., Jensen, M.E., Snyder, R., 2005. The
 826 ASCE standardized reference evapotranspiration equation. *American Society of Civil
 827 Engineers*, Reston.
- 828 Allison, S.D., Wallenstein, M.D., Bradford, M.A., 2010. Soil-carbon response to warming
 829 dependent on microbial physiology. *Nature Geoscience* 3, 336–340.
 830 doi:10.1038/ngeo846
- 831 Ammann, C., Flechard, C.R., Leifeld, J., Neftel, A., Fuhrer, J., 2007. The carbon budget of newly
 832 established temperate grassland depends on management intensity. *Agriculture,
 833 Ecosystems & Environment* 121, 5–20. doi:10.1016/j.agee.2006.12.002
- 834 Ascough, J.C., McMaster, G.S., Andales, A.A., Hansen, N.C., Sherrod, L.A., 2007. Evaluating
 835 GPFARM crop growth, soil water and soil nitrogen components for Colorado dryland
 836 locations. *Transactions of the ASABE* 50, 1565–1578.
- 837 Aubinet, M., Vesala, T., Papale, D., 2012. *Eddy covariance: A practical guide to measurement and
 838 data analysis*. Springer, Dordrecht.
- 839 Bahn, M., Rodeghiero, M., Anderson-Dunn, M., Dore, S., Gimeno, C., Drolesler, M., Williams, M.,
 840 Ammann, C., Berninger, F., Flechard, C., Jones, S., Balzarolo, M., Kumar, S., Newesely, C.,
 841 Priwitzer, T., Raschi, A., Siegwolf, R., Susiluoto, S., Tenhunen, J., Wohlfahrt, G., Cernusca,
 842 A., 2008. Soil respiration in European grasslands in relation to climate and assimilate
 843 supply. *Ecosystems* 11, 1352–1367. doi:10.1007/s10021-008-9198-0
- 844 Baker, I.T., Prihodko, L., Denning, A.S., Goulden, M., Miller, S., da Rocha, H.R., 2008. Seasonal
 845 drought stress in the Amazon: Reconciling models and observations. *Journal of
 846 Geophysical Research* 113, G00B01. doi:10.1029/2007JG000644
- 847 Ball, B.C., 2013. Soil structure and greenhouse gas emissions: a synthesis of 20 years of
 848 experimentation. *European Journal of Soil Science* 64, 357–373. doi:10.1111/ejss.12013
- 849 Balogh, J., Pintér, K., Fóti, S., Cserhalmi, D., Papp, M., Nagy, Z., 2011. Dependence of soil
 850 respiration on soil moisture, clay content, soil organic matter, and CO₂ uptake in dry
 851 grasslands. *Soil Biology and Biochemistry* 43, 1006–1013.
 852 doi:10.1016/j.soilbio.2011.01.017
- 853 Ben Touhami, H., Lardy, R., Barra, V., 2012a. Bayesian calibration of the Pasture Simulation Model
 854 (PaSim) to simulate European grasslands under climate extremes: case study at Stubai
 855 (Austria). *11th PSAM & ESREL Conference*, 25-29 June, Helsinki, Finland, 1, 567-577.
- 856 Ben Touhami, H., Lardy, R., Gilgen, A., Buchmann, N., Bellocchi, G., 2012b. Bayesian calibration of
 857 the Pasture Simulation Model (PaSim) to simulate Swiss grasslands under climate
 858 extremes. *12th Congress of the European Society for Agronomy*, 20-24 August, Helsinki,

- 1
2
3
4 859 Finland, 441-5.
5 860 Ben Touhami, H.B., Lardy, R., Barra, V., Bellocchi, G., 2013. Screening parameters in the Pasture
6 Simulation model using the Morris method. Ecological Modelling 266, 42–57.
7 862 doi:10.1016/j.ecolmodel.2013.07.005
8 863 Bennett, N.D., Croke, B.F.W., Guariso, G., Guillaume, J.H.A., Hamilton, S.H., Jakeman, A.J.,
9 Marsili-Libelli, S., Newham, L.T.H., Norton, J.P., Perrin, C., Pierce, S.A., Robson, B., Seppelt,
10 Voinov, A.A., Fath, B.D., Andreassian, V., 2013. Characterising performance of
11 environmental models. Environmental Modelling & Software 40, 1–20.
12 866 doi:10.1016/j.envsoft.2012.09.011
13 867
14 868 Bondeau, A., Kicklighter, D.W., Kaduk, J., The Participants of the Potsdam Ndp Model
15 intercomparison, 1999. Comparing global models of terrestrial net primary productivity
16 (NPP): importance of vegetation structure on seasonal NPP estimates. Global Change
17 Biology 5, 35–45. doi:10.1046/j.1365-2486.1999.00005.x
18 870 Bondeau, A., Smith, P.C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., 2007.
19 Modelling the role of agriculture for the 20th century global terrestrial carbon balance.
20 Global Change Biology 13, 679–706. doi:10.1111/j.1365-2486.2006.01305.x
21 872
22 873
23 874
24 875 Bos, J.F.F., Pflimlin, A., Aarts, H.F.M., Vertès, F., 2005. Nutrient management at farm scale. How to
25 attain policy objectives in regions with intensive dairy farming? Plant Research
26 International Report 83, Plant Research International, Wageningen, 260 pp.
27 877
28 878 Bright, K.P., Sherlock, R.A., Lile, J., Wastney, M.E., 2000. Development and use of a whole farm
29 model for dairying. In: Halloy, S., Williams, T. (Eds.), Applied complexity - from neural
30 nets to managed landscapes. NZ Institute for Crop and Food Research, Christchurch, pp.
31 382-389.
32 881
33 882 Brisson, N., Gary, C., Justes, E., Roche, R., Mary, B., Ripoche, D., Zimmer, D., Sierra, J., Bertuzzi, P.,
34 Burger, P., 2003. An overview of the crop model STICS. European Journal of Agronomy 18,
35 309–332. doi:10.1016/S1161-0301(02)00110-7
36 884
37 885 Butler, M.P., Davis, K.J., Denning, A.S., Kawa, S.R., 2010. Using continental observations in global
38 atmospheric inversions of CO₂: North American carbon sources and sinks. Tellus B 62,
39 550–572. doi:10.1111/j.1600-0889.2010.00501.x
40 887
41 888 Byrne, K.A., Kiely, G., 2006. Partitioning of Respiration in an Intensively Managed Grassland. Plant
42 and Soil 282, 281–289. doi:10.1007/s11104-005-6065-z
43 889
44 890 Calanca, P., Vuichard, N., Campbell, C., Viovy, N., Cozic, A., Fuhrer, J., Soussana, J.F., 2007.
45 Simulating the fluxes of CO₂ and N₂O in European grasslands with the Pasture Simulation
46 Model (PaSim). Agriculture Ecosystems & Environment 121, 164–174. doi:
47 10.1016/j.agee.2006.12.010
48 893
49 894 Campbell, G.S., 1985. Soil physics with BASIC: transport models for soil-plant systems. Elsevier,
50 Amsterdam.
51 895
52 896 Cantarel, A.A.M., Bloor, J.M.G., Pommier, T., Guillaumaud, N., Moirot, C., Soussana, J.-F., Poly, F.,
53 2012. Four years of experimental climate change modifies the microbial drivers of N₂O
54 fluxes in an upland grassland ecosystem. Global Change Biology 18, 2520–2531.
55 898
56 899 doi:10.1111/j.1365-2486.2012.02692.x
57 900 Chang, J., Viovy, N., Vuichard, N., Ciais, P., Wang, T., Cozic, A., Lardy, R., Graux, A.-I., Klumpp, K.,
58 Martin, R., Soussana, J.-F., 2013. Incorporating grassland management in a global
59 vegetation model: model description and evaluation at 11 eddy-covariance sites in
60 902
61
62

- 1
2
3
4 903 Europe. Geoscientific Model Development Discussions 6, 2769–2812.
5 904 doi:10.5194/gmdd-6-2769-2013
6 905 Chen, D.-X., Hunt, H.W., Morgan, J.A., 1996. Responses of a C3 and C4 perennial grass to CO₂
7 906 enrichment and climate change: Comparison between model predictions and
8 907 experimental data. Ecological Modelling 87, 11–27. doi:10.1016/0304-3800(94)00199-5
9 908 Chirinda, N., Kracher, D., Lægdsmand, M., Porter, J.R., Olesen, J.E., Petersen, B.M., Doltra, J., Kiese,
10 909 R., Butterbach-Bahl, K., 2011. Simulating soil N₂O emissions and heterotrophic CO₂
11 910 respiration in arable systems using FASSET and MoBiLE-DNDC. Plant and Soil 343,
12 911 139–160. doi:10.1007/s11104-010-0596-7
13 912 Churkina, G., Running, S.W., Schloss, A.L., The Participants of the Potsdam Ndp Model
14 913 intercomparison, 1999. Comparing global models of terrestrial net primary productivity
15 914 (NPP): the importance of water availability. Global Change Biology 5, 46–55.
16 915 doi:10.1046/j.1365-2486.1999.00006.x
17 916 Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., Aubinet, M., Buchmann, N.,
18 917 Bernhofer, C., Carrara, A., Chevallier, F., De Noblet, N., Friend, A.D., Friedlingstein, P.,
19 918 Grünwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G.,
20 919 Matteucci, G., Miglietta, F., Ourcival, J.M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G.,
21 920 Soussana, J.F., Sanz, M.J., Schulze, E.D., Vesala, T., Valentini, R., 2005. Europe-wide
22 921 reduction in primary productivity caused by the heat and drought in 2003. Nature 437,
23 922 529–533. doi:10.1038/nature03972
24 923 Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway,
25 924 J., Heimann, M., Jones, C., Le Quéré, C., Myneni, R.B., Piao S., Thornton, P., 2013. Carbon
26 925 and other biogeochemical cycles. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen,
27 926 S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013:
28 927 The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment
29 928 Report of the Intergovernmental Panel on Climate Change. Cambridge University Press,
30 929 Cambridge, pp. 465–570. <<http://www.ipcc.ch/report/ar5/wg1>>
31 930 Ciais, P., Soussana, J.F., Vuichard, N., Luyssaert, S., Don, A., Janssens, I.A., Piao, S.L., Dechow, R.,
32 931 Lathiére, J., Maignan, F., Wattenbach, M., Smith, P., Ammann, C., Freibauer, A., Schulze,
33 932 E.D., the CARBOEUROPE Synthesis Team, 2010. The greenhouse gas balance of
34 933 European grasslands. Biogeosciences Discussions 7, 5997–6050.
35 934 doi:10.5194/bgd-7-5997-2010
36 935 De Jager, J.M., 1994. Accuracy of vegetation evaporation ratio formulae for estimating final wheat
37 936 yield. Water SA 20, 307–314.
38 937 De Martonne, E., 1942. Nouvelle carte mondiale de l'indice d'aridité. Annales de Géographie 51,
39 938 242-250 (in French).
40 939 Desai, A.R., Richardson, A.D., Moffat, A.M., Kattge, J., Hollinger, D.Y., Barr, A., Falge, E., Noormets,
41 940 A., Papale, D., Reichstein, M., Stauch, V.J., 2008. Cross-site evaluation of eddy covariance
42 941 GPP and RE decomposition techniques. Agricultural and Forest Meteorology 148,
43 942 821-838. doi:10.1016/j.agrformet.2007.11.012
44 943 Diodato, N., Ceccarelli, M., 2004. Multivariate indicator Kriging approach using a GIS to classify
45 944 soil degradation for Mediterranean agricultural lands. Ecological Indicators 4, 177–187.
46 945 doi:10.1016/j.ecolind.2004.03.002
47 946 Donatelli, M., Cerrani, I., Fanchini, D., Fumagalli, D., Rizzoli, A.E., 2012. Enhancing model reuse via

- 1
2
3
4 947 component-centered modeling frameworks: the vision and example realizations. In:
5 Seppelt, R., Voinov, A.A., Lange, S., Bankamp, D. (Eds.), Proceedings of International
6 Congress on Environmental Modelling and Software Managing Resources of a Limited
7 Planet, Sixth Biennial Meeting, Leipzig, Germany, pp. 1185–1192.
8
9 951 Duru, M., Jouany, C., Le Roux, X., Navas, M.L., Cruz, P., 2013. From a conceptual framework to an
10 operational approach for managing grassland functional diversity to obtain targeted
11 ecosystem services: Case studies from French mountains. *Renewable Agriculture and
12 Food Systems* 23, 239–254. doi:10.1017/S1742170513000306
13
14 955 EC, 2008. Regulation (EC) No 1166/2008 of the European Parliament and of the Council of 19
15 November 2008 on farm structure surveys and the survey on agricultural production
16 methods and repealing Council Regulation (EEC). *Official Journal of the European Union*,
17 Brussels.
18
19 959 Flechard, C.R., Ambus, P., Skiba, U., Rees, R.M., Hensen, A., van Amstel, A., Dasselaar, A. van den
20 P., Soussana, J.F., Jones, M., Clifton-Brown, J., Raschi, A., Horvath, L., Neftel, A., Jocher,
21 M., Ammann, C., Leifeld, J., Fuhrer, J., Calanca, P., Thalman, E., Pilegaard, K., Di Marco, C.,
22 Campbell, C., Nemitz, E., Hargreaves, K.J., Levy, P.E., Ball, B.C., Jones, S.K., van de Bulk,
23 W.C.M., Groot, T., Blom, M., Domingues, R., Kasper, G., Allard, V., Ceschia, E., Cellier, P.,
24 Laville, P., Henault, C., Bizouard, F., Abdalla, M., Williams, M., Baronti, S., Berretti, F.,
25 Grosz, B., 2007. Effects of climate and management intensity on nitrous oxide emissions
26 in grassland systems across Europe. *Agriculture, Ecosystems & Environment* 121,
27 135–152. doi:10.1016/j.agee.2006.12.024
28
29 968 Fox, D.G., 1981. Judging air quality model performance. *Bulletin of the American Meteorological
30 Society* 62, 599–609.
31 doi:[http://dx.doi.org/10.1175/1520-0477\(1981\)062<0599:JAQMP>2.0.CO;2](http://dx.doi.org/10.1175/1520-0477(1981)062<0599:JAQMP>2.0.CO;2)
32
33 971 Gilmanov, T.G., Aires, L., Barcza, Z., Baron, V.S., Belelli, L., Beringer, J., Billesbach, D., Bonal, D.,
34 Bradford, J., Ceschia, E., Cook, D., Corradi, C., Frank, A., Ganelle, D., Gimeno, C.,
35 Gruenwald, T., Guo, H., Hanan, N., Haszpra, L., Heilman, J., Jacobs, A., Jones, M.B.,
36 Johnson, D.A., Kiely, G., Li, S., Magliulo, V., Moors, E., Nagy, Z., Nasirov, M., Owensby, C.,
37 Pinter, K., Pio, C., Reichstein, M., Sanz, M.J., Scott, R., Soussana, J.F., Stoy, P.C., Svejcar, T.,
38 Tuba, Z., Zhou, G., 2010. Productivity, respiration, and light-response parameters of
39 world grassland and agroecosystems derived from flux-tower measurements. *Rangeland
40 Ecology & Management* 63, 16–39. doi:10.2111/REM-D-09-00072.1
41
42 979 Giraldo, L.M., Lizcano, L.J., Gijsman, A.J., Rivera, B., Franco, L.H., 1999. Adapting the CROPGRO
43 model of DSSAT to simulate the growth of Brachiaria decumbens. In: *Proceedings of The
44 Third International Symposium on Systems Approaches for Agricultural Development*.
45 Lima, Peru, pp. 1–10.
46
47 983 Graux, A.-I., Bellocchi, G., Lardy, R., Soussana, J.-F., 2013. Ensemble modelling of climate change
48 risks and opportunities for managed grasslands in France. *Agricultural and Forest
49 Meteorology* 170, 114–131. doi:10.1016/j.agrformet.2012.06.010
50
51 986 Graux, A.I., Gaurut, M., Agabriel, J., Baumont, R., Delagarde, R., Delaby, L., Soussana, J.F., 2011.
52 Development of the Pasture Simulation Model for assessing livestock production under
53 climate change. *Agriculture, Ecosystems & Environment* 144, 69–91. doi:
54 10.1016/j.agee.2011.07.001
55
56 990 Graux, A.-I., Lardy, R., Bellocchi, G., Soussana, J.-F., 2012. Global warming potential of French
57
58
59
60
61
62
63
64
65

- 1
2
3
4 991 grassland-based dairy livestock systems under climate change. *Regional Environmental*
5 992 *Change* 12, 751–763. doi:10.1007/s10113-012-0289-2
6
7 993 Hagen, S.C., Braswell, B.H., Linder, E., Frolking, S., Richardson, A.D., Hollinger, D.Y., 2006. Statistical
8 994 uncertainty of eddy flux-based estimates of gross ecosystem carbon exchange at
9 995 Howland Forest, Maine. *Journal of Geophysical Research* 111, D08S03.
10 996 doi:10.1029/2005JD006154.
11
12 997 Hidy, D., Barcza, Z., Haszpra, L., Churkina, G., Pintér, K., Nagy, Z., 2012. Development of the
13 998 Biome-BGC model for simulation of managed herbaceous ecosystems. *Ecological*
14 999 *Modelling* 226, 99–119. doi:10.1016/j.ecolmodel.2011.11.008
15
16 1000 Hollinger, D.Y., Richardson, A.D., 2005. Uncertainty in eddy covariance measurements and its
17 1001 application to physiological models. *Tree Physiology* 25, 873–885.
18 1002 doi:10.1093/treephys/25.7.873
19
20 1003 Holzwirth, D.P., Huth, N.I., deVoil, P.G., Zurcher, E.J., Herrmann, N.I., McLean, G., Chenu, K., van
21 1004 Oosterom, E., Snow, V.O., Murphy, C., Moore, A.D., Brown, H.E., Whish, J.P.M., Verrall, S.,
22 1005 Fainges, J., L.W., B., Peake, A.S., Poulton, P.L., Hochman, Z., Thorburn, P.J., Gaydon, D.S.,
23 1006 Dalglish, N.P., Rodriguez, D., Cox, H., Chapman, S., Doherty, A., Teixeira, E., Sharp, J.,
24 1007 Cichota, R., Vogeler, I., Li, F.Y., Wang, E., Hammer, G.L., Robertson, M.J., Dimes, J.,
25 1008 Carberry, P.S., Hargreaves, J.N.G., MacLeod, N., McDonald, C., Harsdorf, J., Wedgwood, S.,
26 1009 Keating, B.A., 2014. APSIM - Evolution towards a new generation of agricultural systems
27 1010 simulation. *Environmental Modelling & Software*, in press.
28 1011 doi:10.1016/j.envsoft.2014.07.009
29
30 1012 Huntzinger, D.N., Post, W.M., Wei, Y., Michalak, A.M., West, T.O., Jacobson, A.R., Baker, I.T., Chen,
31 1013 J.M., Davis, K.J., Hayes, D.J., Hoffman, F.M., Jain, A.K., Liu, S., McGuire, A.D., Neilson, R.P.,
32 1014 Potter, C., Poulter, B., Price, D., Racská, B.M., Tian, H.Q., Thornton, P., Tomelleri, E., Viovy,
33 1015 N., Xiao, J., Yuan, W., Zeng, N., Zhao, M., Cook, R., 2012. North American Carbon Program
34 1016 (NACP) regional interim synthesis: Terrestrial biospheric model intercomparison.
35 1017 *Ecological Modelling* 232, 144–157. doi:10.1016/j.ecolmodel.2012.02.004
36
37 1018 Hussain, M.Z., Gruenwald, T., Tenhunen, J.D., Li, Y.L., Mirzae, H., Bernhofer, C., Otieno, D., Dinh,
38 1019 N.Q., Schmidt, M., Wartinger, M., Owen, K., 2011. Summer drought influence on CO₂ and
39 1020 water fluxes of extensively managed grassland in Germany. *Agriculture, Ecosystems &*
40 1021 *Environment* 141, 67–76. doi:10.1016/j.agee.2011.02.013
41
42 1022 Jacobs, C.M.J., Jacobs, A.F.G., Bosveld, F.C., Hendriks, D.M.D., Hensen, A., Kroon, P.S., Moors, E.J.,
43 1023 Nol, L., Schrier-Uijl, A., Veenendaal, E.M., 2007. Variability of annual CO₂ exchange from
44 1024 Dutch grasslands. *Biogeosciences* 4, 803–816. doi:10.5194/bg-4-803-2007
45
46 1025 Janssens, I.A., Freibauer, A., Schlamadinger, B., Ceulemans, R., Ciais, P., Dolman, A.J., Heimann, M.,
47 1026 Nabuurs, G.-J., Smith, P., Valentini, R., 2005. The carbon budget of terrestrial ecosystems
48 1027 at country-scale – a European case study. *Biogeosciences* 2, 15–26.
49 1028 doi:10.5194/bg-2-15-2005
50
51 1029 Johnson, I.R., Chapman, D.F., Snow, V.O., Eckard, R.J., Parsons, A.J., Lambert, M.G., Cullen, B.R.,
52 1030 2008. DairyMod and EcoMod: biophysical pasture-simulation models for Australia and
53 1031 New Zealand. *Australian Journal of Experimental Agriculture* 48, 621–631.
54 1032 doi:10.1071/EA07133
55
56 1033 Jung, M., Reichstein, M., Margolis, H.A., Cescatti, A., Richardson, A.D., Arain, M.A., Arneth, A.,
57 1034 Bernhofer, C., Bonal, D., Chen, J., Gianelle, D., Gobron, N., Kiely, G., Kutsch, W., Lasslop,

- 1
2
3
4 1035 G., Law, B.E., Lindroth, A., Merbold, L., Montagnani, L., Moors, E.J., Papale, D.,
5 1036 Sottocornola, M., Vaccari, F., Williams, C., 2011. Global patterns of land-atmosphere
6 1037 fluxes of carbon dioxide, latent heat, and sensible heat derived from eddy covariance,
7 1038 satellite, and meteorological observations. *Journal of Geophysical Research* 116, G00J07.
8 1039 doi:10.1029/2010JG001566
9
10 1040 Jung, M., Vetter, M., Herold, M., Churkina, G., Reichstein, M., Zaehle, S., Ciais, P., Viovy, N.,
11 1041 Bondeau, A., Chen, Y., Trusilova, K., Feser, F., Heimann, M., 2007. Uncertainties of
12 1042 modeling gross primary productivity over Europe: A systematic study on the effects of
13 1043 using different drivers and terrestrial biosphere models. *Global Biogeochemical Cycles* 21,
14 1044 GB4021. doi:10.1029/2006GB002915
15
16 1045 Klumpp, K., Tallec, T., Guix, N., Soussana, J.-F., 2011. Long-term impacts of agricultural practices
17 1046 and climatic variability on carbon storage in a permanent pasture. *Global Change Biology*
18 1047 17, 3534–3545. doi:10.1111/j.1365-2486.2011.02490.x
19
20 1048 Krinner, G., Viovy, N., de Noblet-Ducoudré, N., Ogée, J., Polcher, J., Friedlingstein, P., Ciais, P., Sitch,
21 1049 S., Prentice, I.C., 2005. A dynamic global vegetation model for studies of the coupled
22 1050 atmosphere-biosphere system. *Global Biogeochemical Cycles* 19, GB1015.
23 1051 doi:10.1029/2003GB002199
24
25 1052 Kroon, P.S., Hensen, A., Jonker, H.J.J., Ouwersloot, H.G., Vermeulen, A.T., Bosveld, F.C., 2009.
26 1053 Uncertainties in eddy covariance flux measurements assessed from CH₄ and N₂O
27 1054 observations. *Agricultural and Forest Meteorology* 150, 806-816. doi:
28 1055 10.1016/j.agrformet.2009.08.008
29
30 1056 Laniak, G.F., Olchin, G., Goodall, J., Voinov, A., Hill, M., Glynn, P., Whelan, G., Geller, G., Quinn, N.,
31 1057 Blind, M., Peckham, S., Reaney, S., Gaber, N., Kennedy, R., Hughes, A., 2013. Integrated
32 1058 environmental modeling: A vision and roadmap for the future. *Environmental Modelling & Software*
33 1059 39, 3–23. doi:10.1016/j.envsoft.2012.09.006
34
35 1060 Lardy, R., Bachelet, B., Bellocchi, G., Hill, D.R.C., 2014. Towards vulnerability minimization of
36 1061 grassland soil organic matter using metamodels. *Environmental Modelling & Software* 52,
37 1062 38–50. doi:10.1016/j.envsoft.2013.10.015
38
39 1063 Lasslop, G., Reichstein, M., Kattge, J., Papale, D., 2008. Influences of observation errors in eddy
40 1064 flux data on inverse model parameter estimation. *Biogeosciences* 5, 1311-1324.
41 1065 doi:doi:10.5194/bg-5-1311-2008
42
43 1066 Liu, M., He, H., Yu, G., Sun, X., Zhang, L., Han, S., Wang, H., Zhou, G., 2012. Uncertainty analysis in
44 1067 data processing on the estimation of net carbon exchanges at different forest ecosystems
45 1068 in China. *Journal of Forest Research* 17, 312–322. doi:10.1007/s10310-011-0323-0
46
47 1069 Luo, G., Han, Q., Zhou, D., Li, L., Chen, X., Li, Y., Hu, Y., Li, B.L., 2012. Moderate grazing can
48 1070 promote aboveground primary production of grassland under water stress. *Ecological
49 1071 Complexity* 11, 126–136. doi:10.1016/j.ecocom.2012.04.004
50
51 1072 Lobell, D.B., Burke, M.B., 2010. On the use of statistical models to predict crop yield
52 1073 responses to climate change. *Agricultural and Forest Meteorology* 150, 1443–1452.
53 1074 doi:10.1016/j.agrformet.2010.07.008
54
55 1075 Martin, G., Martin-Clouaire, R., Rellier, J.P., Duru, M., 2011. A simulation framework for the
56 1076 design of grassland-based beef-cattle farms. *Environmental Modelling & Software* 26,
57 1077 371–385. doi:10.1016/j.envsoft.2010.10.002
58
59 1078 Migliavacca, M., Reichstein, M., Richardson, A.D., Colombo, R., Sutton, M.A., Lasslop, G.,
60
61
62
63
64
65

- 1
2
3
4 1079 Tomelleri, E., Wohlfahrt, G., Carvalhais, N., Cescatti, A., Mahecha, M.D., Montagnani, L.,
5 1080 Papale, D., Zaehle, S., Arain, A., Arneth, A., Black, T.A., Carrara, A., Dore, S., Gianelle, D.,
6 1081 Helfter, C., Hollinger, D., Kutsch, W.L., Lafleur, P.M., Nouvellon, Y., Rebmann, C., Da
7 1082 ROCHA, H.R., Rodeghiero, M., Roupsard, O., Sebastià, M.-T., Seufert, G., Soussana, J.-F.,
8 1083 Van Der MOLEN, M.K., 2011. Semiempirical modeling of abiotic and biotic factors
9 1084 controlling ecosystem respiration across eddy covariance sites. *Global Change Biology* 17,
10 1085 390–409. doi:10.1111/j.1365-2486.2010.02243.x
11
12 1086 Minunno, F., Peltoniemi, M., Launiainen, S., Mäkelä, A., 2014. Integrating ecosystems
13 1087 measurements from multiple eddy-covariance sites to a simple model of ecosystem
14 1088 process - Are there possibilities for a uniform model calibration? *Geophysical Research
15 Abstracts* 16, EGU2014-10706-3.
16
17 1089 Monteith, J., 1965. Evaporation and environment. *Symposium of the Society for Experimental
18 Biology* 19, 205–234.
19
20 1090 Moriasi, D., Arnold, J., Van Liew, M., Bingner, R., Harmel, R., Veith, T., 2007. Model evaluation
21 1091 guidelines for systematic quantification of accuracy in watershed simulations.
22 1092 *Transactions of the ASABE* 50, 885–900.
23
24 1093 Moyano, F.E., Vasilyeva, N., Bouckaert, L., Cook, F., Craine, J., Curiel Yuste, J., Don, A., Epron, D.,
25 1094 Formanek, P., Franzluebbers, A., Ilstedt, U., Kätterer, T., Orchard, V., Reichstein, M., Rey,
26 1095 A., Ruamps, L., Subke, J.-A., Thomsen, I.K., Chenu, C., 2012. The moisture response of soil
27 1096 heterotrophic respiration: interaction with soil properties. *Biogeosciences* 9, 1173–1182.
28 1097 doi:10.5194/bg-9-1173-2012
29
30 1098 Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I — A
31 1099 discussion of principles. *Journal of Hydrology* 10, 282–290.
32 1100 doi:10.1016/0022-1694(70)90255-6
33
34 1101 Palosuo, T., Kersebaum, K.C., Angulo, C., Hlavinka, P., Moriondo, M., Olesen, J.E., Patil, R.H., Ruget,
35 1102 F., Rumbaur, C., Takac, J., Trnka, M., Bindi, M., caldag, B., Ewert, F., Ferrise, R., Mirschel,
36 1103 W., Saylan, L., Siska, B., Roeter, R., 2011. Simulation of winter wheat yield and its
37 1104 variability in different climates of Europe: A comparison of eight crop growth models.
38 1105 *European Journal of Agronomy* 35, 103–114. doi: 10.1016/j.eja.2011.05.001
39
40 1106 Papale, D., Reichstein, M., Aubinet, M., Canfora, E., Bernhofer, C., Longdoz, B., Kutsch, W., Rambal,
41 1107 S., Valentini, R., Vesala, T., Yakir, D., 2006. Towards a standardized processing of net
42 1108 ecosystem exchange measured with eddy covariance technique: algorithms and
43 1109 uncertainty estimation. *Biogeosciences* 3, 571–583. doi:10.5194/bg-3-571-2006
44
45 1110 Parton, W.J., 1988. Dynamics of C, N, P and S in grassland soils: a model. *Biogeochemistry* 5,
46 1111 109–131. doi:10.1007/BF02180320
47
48 1112 Parton, W.J., Morgan, J.A., Wang, G., Del Grosso, S., 2007. Projected ecosystem impact of the
49 1113 Prairie Heating and CO₂ Enrichment experiment. *New Phytologist* 174, 823–834.
50 1114 doi:10.1111/j.1469-8137.2007.02052.x
51
52 1115 Peichl, M., Carton, O., Kiely, G., 2012. Management and climate effects on carbon dioxide and
53 1116 energy exchanges in a maritime grassland. *Agriculture, Ecosystems & Environment* 158,
54 1117 132–146. doi:10.1016/j.agee.2012.06.001
55
56 1118 Pintér, K., Barcza, Z., Balogh, J., Czóbel, S., Csíntalan, Z., Tuba, Z., Nagy, Z., 2008. Interannual
57 1119 variability of grasslands' carbon balance depends on soil type. *Community Ecology* 9,
58 1120 43–48. doi:10.1556/ComEc.9.2008.S.7
59
60
61
62
63
64
65

- 1
2
3
4 Prescher, A.-K., Grünwald, T., Bernhofer, C., 2010. Land use regulates carbon budgets in eastern
5 Germany: From NEE to NBP. *Agricultural and Forest Meteorology* 150, 1016–1025.
6 doi:10.1016/j.agrformet.2010.03.008
7
8 Rafique, R., Peichl, M., Hennessy, D., Kiely, G., 2011. Evaluating management effects on nitrous
9 oxide emissions from grasslands using the process-based DeNitrification–DeComposition
10 (DNDC) model. *Atmospheric Environment* 45, 6029–6039.
11 doi:10.1016/j.atmosenv.2011.07.046
12
13 Refsgaard, J.C., van der Sluijs, J.P., Højberg, A.L., Vanrolleghem, P.A., 2007. Uncertainty in the
14 environmental modelling process – A framework and guidance. *Environmental Modelling
15 & Software* 22, 1543–1556. doi:10.1016/j.envsoft.2007.02.004
16
17 Reichstein, M., Bahn, M., Ciais, P., Frank, D., Mahecha, M.D., Seneviratne, S.I., Zscheischler, J.,
18 Beer, C., Buchmann, N., Frank, D.C., Papale, D., Rammig, A., Smith, P., Thonicke, K., van
19 der Velde, M., Vicca, S., Walz, A., Wattenbach, M., 2013. Climate extremes and the
20 carbon cycle. *Nature* 500, 287–295. doi:10.1038/nature12350
21
22 Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C.,
23 Buchmann, N., Gilmanov, T., Granier, A., Grünwald, T., Havrankova, K., Ilvesniemi, H.,
24 Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T.,
25 Miglietta, F., Ourcival, J.-M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen,
26 J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., Valentini, R., 2005. On the separation of net
27 ecosystem exchange into assimilation and ecosystem respiration: review and improved
28 algorithm. *Global Change Biology* 11, 1424–1439.
29 doi:10.1111/j.1365-2486.2005.001002.x
30
31 Richardson, A.D., Aubinet, M., Barr, A.G., Hollinger, D.Y., Ibrom, A., Lasslop, G., Reichstein, M.,
32 2012, Uncertainty quantification. In: Aubinet, M., Vesala, T., Papale, D. (Eds.), *Eddy
33 covariance - A practical guide to measurement and data analysis*. Springer, Dordrecht, pp.
34 173–209.
35
36 Richardson, A.D., Williams, M., Hollinger, D.Y., Moore, D.J.P., Dail, D.B., Davidson, E.A., Scott, N.A.,
37 Evans, R.S., Hughes, H., Lee, J.T., Rodrigues, C., Savage, K., 2010. Estimating parameters of
38 a forest ecosystem C model with measurements of stocks and fluxes as joint constraints.
39 *Oecologia* 164, 25–40. doi:10.1007/s00442-010-1628-y
40
41 Riedo, M., Grub, A., Rosset, M., Fuhrer, J., 1998. A pasture simulation model for dry matter
42 production, and fluxes of carbon, nitrogen, water and energy. *Ecological Modelling* 105,
43 141–183. doi:10.1016/S0304-3800(97)00110-5
44
45 Riedo, M., Milford, C., Schmid, M., Sutton, M.A., 2002. Coupling soil-plant-atmosphere exchange
46 of ammonia with ecosystem functioning in grasslands. *Ecological Modelling* 158, 83–110.
47 doi:10.1016/S0304-3800(02)00169-2
48
49 Rodriguez, D., Van Oijen, M., Schapendonk, A., 1999. LINGRA-CC: a sink–source model to
50 simulate the impact of climate change and management on grassland productivity. *New
51 Phytologist* 144, 359–368. doi:10.1046/j.1469-8137.1999.00521.x
52
53 Rötter, R.P., Palosuo, T., Kersebaum, K.C., Angulo, C., Bindl, M., Ewert, F., Ferrise, R., Hlavinka, P.,
54 Moriondo, M., Nendel, C., Olesen, J.E., Patil, R.H., Ruget, F., Takac, J., Trnka, M., 2012.
55 Simulation of spring barley yield in different climatic zones of Northern and Central
56 Europe: A comparison of nine crop models. *Field Crops Research* 133, 23–36.
57
58 doi:10.1016/j.fcr.2012.03.016
59
60
61
62
63
64 Comment citer ce document :
65 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

- 1
2
3
4 1167 Ruget, F., Satger, S., Volaire, F., Lelièvre, F., 2009. Modeling tiller density, growth, and yield of
5 Mediterranean perennial grasslands with STICS. *Crop Science* 49, 2379–2385.
6 doi:doi:10.2135/cropsci2009.06.0323
7
8 1170 Schaefer, K., Schwalm, C.R., Williams, C., Arain, M.A., Barr, A., Chen, J.M., Davis, K.J., Dimitrov, D.,
9 Hilton, T.W., Hollinger, D.Y., Humphreys, E., Poulter, B., Racza, B.M., Richardson, A.D.,
10 Sahoo, A., Thornton, P., Vargas, R., Verbeeck, H., Anderson, R., Baker, I., Black, T.A.,
11 Bolstad, P., Chen, J., Curtis, P.S., Desai, A.R., Dietze, M., Dragoni, D., Gough, C., Grant, R.F.,
12 Gu, L., Jain, A., Kucharik, C., Law, B., Liu, S., Lokipitiya, E., Margolis, H.A., Matamala, R.,
13 McCaughey, J.H., Monson, R., Munger, J.W., Oechel, W., Peng, C., Price, D.T., Ricciuto, D.,
14 Riley, W.J., Roulet, N., Tian, H., Tonitto, C., Torn, M., Weng, E., Zhou, X., 2012. A
15 model-data comparison of gross primary productivity: Results from the North American
16 Carbon Program site synthesis. *Journal of Geophysical Research* 117, G03010.
17 doi:10.1029/2012JG001960
18
19 1179 Schapendonk, A.H.C.M., Stol, W., van Kraalingen, D.W.G., Bouman, B.A.M., 1998. LINGRA, a
20 sink/source model to simulate grassland productivity in Europe. *European Journal of*
21 *Agronomy* 9, 87–100. doi:10.1016/S1161-0301(98)00027-6
22
23 1180 Schmid, M., Fuhrer, J., Neftel, A., 2001a. Nitrous oxide concentrations in the soil of a mown
24 grassland: comparison of model results with soil profile measurements. *Water, Air, & Soil*
25 *Pollution: Focus* 1, 437–446. doi:10.1023/A:1013158028103
26
27 1181 Schmid, M., Neftel, A., Riedo, M., Fuhrer, J., 2001b. Process-based modelling of nitrous oxide
28 emissions from different nitrogen sources in mown grassland. *Nutrient Cycling in*
29 *Agroecosystems* 60, 177–187. doi:10.1023/a:1012694218748
30
31 1182 Schmitt, M., Bahn, M., Wohlfahrt, G., Tappeiner, U., Cernusca, A., 2010. Land use affects the net
32 ecosystem CO₂ exchange and its components in mountain grasslands. *Biogeosciences* 7,
33 2297–2309. doi:10.5194/bg-7-2297-2010
34
35 1183 Schulze, E.D., Luyssaert, S., Ciais, P., Freibauer, A., Al, I.A.J. et, Schulze, E.D., Soussana, J.F., Smith,
36 P., Grace, J., Levin, I., Thiruchittampalam, B., Heimann, M., Dolman, A.J., Valentini, R.,
37 Bousquet, P., Peylin, P., Peters, W., Rödenbeck, C., Etiope, G., Vuichard, N., Wattenbach,
38 M., Nabuurs, G.J., Poussi, Z., Nieschulze, J., Gash, J.H., Schulze, E.D., Soussana, J.F., Smith,
39 P., Grace, J., Levin, I., Thiruchittampalam, B., Heimann, M., Dolman, A.J., Valentini, R.,
40 Bousquet, P., Peylin, P., Peters, W., Rödenbeck, C., Etiope, G., Vuichard, N., Wattenbach,
41 M., Nabuurs, G.J., Poussi, Z., Nieschulze, J., Gash, J.H., 2009. Importance of methane and
42 nitrous oxide for Europe's terrestrial greenhouse-gas balance. *Nature Geoscience* 2,
43 842–850. doi:10.1038/ngeo686
44
45 1184 Scurlock, J.M.O., Hall, D.O., 1998. The global carbon sink: a grassland perspective. *Global Change*
46 *Biology* 4, 229–233. doi:10.1046/j.1365-2486.1998.00151.x
47
48 1185 Sheikh, V., Visser, S., Stroosnijder, L., 2009. A simple model to predict soil moisture: Bridging
49 Event and Continuous Hydrological (BEACH) modelling. *Environmental Modelling &*
50 *Software* 24, 542–556. doi:10.1016/j.envsoft.2008.10.005
51
52 1186 Shuttleworth, W.J., Wallace, J.S., 1985. Evaporation from sparse crops—an energy combination
53 theory. *Quarterly Journal of the Royal Meteorological Society* 111, 839–855.
54 doi:10.1002/qj.49711146910
55
56 1187 Snow, V.O., Rotz, C.A., Moore, A.D., Martin-Clouaire, R., Johnson, I.R., Hutchings, N.J., Eckard, R.J.,
57 2014. The challenges – and some solutions – to process-based modelling of grazed
58
59 1188
60
61

- 1
2
3
4 1211 agricultural systems. *Environmental Modelling & Software*, 62, 420-436.
5 1212 doi:10.1016/j.envsoft.2014.03.009
6 1213 Soussana, J.-F., Fuhrer, J., Jones, M., Van Amstel, A., 2007. The greenhouse gas balance of
7 grasslands in Europe. *Agriculture, Ecosystems & Environment* 121, 1–4.
8 1214 doi:10.1016/j.agee.2006.12.001
9 1215 Stöckle, C.O., Donatelli, M., Nelson, R., 2003. CropSyst, a cropping systems simulation model.
10 European Journal of Agronomy 18, 289–307. doi:10.1016/S1161-0301(02)00109-0
11 1216 Suttie, J.M., Reynolds, S.G., Batello, C., 2005. Grasslands of the world. Food and Agricultural
12 Organization of the United Nations, Rome.
13 1217 Suttle, K.B., Thomsen, M.A., Power, M.E., 2007. Species interactions reverse grassland responses
14 to changing climate. *Science* 315, 640–642. doi:10.1126/science.1136401
15 1218 Thornley, J.H.M., 1998. Dynamic model of leaf photosynthesis with acclimation to light and
16 nitrogen. *Annals of Botany* 81, 421–430. doi:10.1006/anbo.1997.0575
17 1219 Trudinger, C.M., Raupach, M.R., Rayner, P.J., Kattge, J., Liu, Q., Pak, B., Reichstein, M., Renzullo, L.,
18 Richardson, A.D., Roxburgh, S.H., Styles, J., Wang, Y.P., Briggs, P., Barrett, D., Nikolova, S.,
19 2007. OptIC project: An intercomparison of optimization techniques for parameter
21 estimation in terrestrial biogeochemical models. *Journal of Geophysical Research* 112.
22 doi:10.1029/2006JG000367
23 1220 Van Oijen, M., Cameron, D.R., Butterbach-Bahl, K., Farahbakhshazad, N., Jansson, P.-E., Kiese, R.,
24 Rahn, K.-H., Werner, C., Yeluripati, J.B., 2011. A Bayesian framework for model calibration,
25 comparison and analysis: Application to four models for the biogeochemistry of a
26 Norway spruce forest. *Agricultural and Forest Meteorology* 151, 1609–1621.
27 doi:10.1016/j.agrformet.2011.06.017
28 1221 Van Oijen, M., Höglind, M., Hanslin, H.M., Caldwell, N., 2005. Process-based modeling of timothy
29 regrowth. *Agronomy Journal* 97, 1295–1303. doi:10.2134/agronj2004.0251
30 1222 Vital, J.-A., Gaurut, M., Lardy, R., Viovy, N., Soussana, J.-F., Bellocchi, G., Martin, R., 2013.
31 High-performance computing for climate change impact studies with the Pasture
32 Simulation model. *Computers and Electronics in Agriculture* 98, 131–135.
33 doi:10.1016/j.compag.2013.08.004
34 1223 Vuichard, N., Ciais, P., Viovy, N., Calanca, P., Soussana, J.-F., 2007a. Estimating the greenhouse gas
35 fluxes of European grasslands with a process-based model: 2. Simulations at the
36 continental level. *Global Biogeochemical Cycles* 21, GB1005. doi:10.1029/2005gb002612
37 1224 Vuichard, N., Soussana, J.-F., Ciais, P., Viovy, N., Ammann, C., Calanca, P., Clifton-Brown, J., Fuhrer,
38 J., Jones, M., Martin, C., 2007b. Estimating the greenhouse gas fluxes of European
39 grasslands with a process-based model: 1. Model evaluation from in situ measurements.
40 Global Biogeochemical Cycles 21, GB1004. doi:10.1029/2005gb002611
41 1225 Wallach, D., Thorburn, P.J., 2014. The error in agricultural systems model prediction depends on
42 the variable being predicted. *Environmental Modelling & Software* 62, 487–494. doi:
43 10.1016/j.envsoft.2014.08.001
44 1226 Wang, J., Cardenas, L.M., Misselbrook, T.H., Cuttle, S., Thorman, R.E., Li, C., 2012. Modelling
45 nitrous oxide emissions from grazed grassland systems. *Environmental Pollution* 162,
46 223–233. doi:10.1016/j.envpol.2011.11.027
47 1227 Wang, Y.-P., Trudinger, C.M., Enting, I.G., 2009. A review of applications of model–data fusion to
48 studies of terrestrial carbon fluxes at different scales. *Agricultural and Forest
49 Meteorology* 145, 1–16. doi:10.1016/j.agrformet.2009.01.001
50 1228 1229 1230 1231 1232 1233 1234 1235 1236 1237 1238 1239 1240 1241 1242 1243 1244 1245 1246 1247 1248 1249 1250 1251 1252 1253 1254

- 1 1255 Meteorology 149, 1829–1842. doi:10.1016/j.agrformet.2009.07.009
- 2 1256 Warmink, J.J., Janssen, J.A.E.B., Booij, M.J., Krol, M.S., 2010. Identification and classification of
3 uncertainties in the application of environmental models. Environmental Modelling &
4 Software 25, 1518–1527. doi:10.1016/j.envsoft.2010.04.011
- 5 1259 Warnant, P., François, L., Strivay, D., Gérard, J.C., 1994. CARAIB: A global model of terrestrial
6 biological productivity. Global Biogeochemical Cycles 8, 255–270.
7 doi:10.1029/94gb00850
- 8 1262 Warszawski, L., Frieler, K., Huber, V., Piontek, F., Serdeczny, O., Schewe, J., 2014. The Inter-Sectoral
9 Impact Model Intercomparison Project (ISI-MIP): Project framework. Proceedings of the
10 National Academy of Sciences 111, 3228–3232. doi:10.1073/pnas.1312330110
- 11 1265 Wattenbach, M., Sus, O., Vuichard, N., Lehuger, S., Gottschalk, P., Li, L., Leip, A., Williams, M.,
12 Tomelleri, E., Kutsch, W.L., Buchmann, N., Eugster, W., Dietiker, D., Aubinet, M., Ceschia,
13 E., Béziat, P., Grünwald, T., Hastings, A., Osborne, B., Ciais, P., Cellier, P., Smith, P., 2010.
14 The carbon balance of European croplands: A cross-site comparison of simulation
15 models. Agriculture, Ecosystems & Environment 139,
16 419–453.doi:10.1016/j.agee.2010.08.004
- 17 1271 Wieder, W.R., Bonan, G.B., Allison, S.D., 2013. Global soil carbon projections are improved by
18 modelling microbial processes. Nature Climate Change 3, 909–912.
19 doi:10.1038/nclimate1951
- 20 1274 Williams, J.R., Jones, C.A., Kiniry, J.R., Spanel, D.A., 1989. The EPIC crop growth model.
21 Transactions of the ASAE 32, 497–511. doi:10.13031/2013.31032
- 22 1276 Willmott, C.J., Wicks, D.E., 1980. An Empirical Method for the Spatial Interpolation of Monthly
23 Precipitation within California. Physical Geography 1, 59–73.
24 doi:10.1080/02723646.1980.10642189
- 25 1279 Wohlfahrt, G., Anderson-Dunn, M., Bahn, M., Balzarolo, M., Berninger, F., Campbell, C., Carrara,
26 A., Cescatti, A., Christensen, T., Dore, S., Eugster, W., Friberg, T., Furger, M., Ganelle, D.,
27 Gimeno, C., Hargreaves, K., Hari, P., Haslwanter, A., Johansson, T., Marcolla, B., Milford, C.,
28 Nagy, Z., Nemitz, E., Rogiers, N., Sanz, M.J., Siegwolf, R.T.W., Susiluoto, S., Sutton, M.,
29 Tuba, Z., Ugolini, F., Valentini, R., Zorer, R., Cernusca, A., 2008. Biotic, abiotic, and
30 management controls on the net ecosystem CO₂ exchange of European mountain
31 grassland ecosystems. Ecosystems 11, 1338–1351. doi:10.1007/s10021-008-9196-2
- 32 1286 Wu, J., van der Linden, L., Lasslop, G., Carvalhais, N., Pilegaard, K., Beier, C., Ibrom, A., 2012.
33 Effects of climate variability and functional changes on the interannual variation of the
34 carbon balance in a temperate deciduous forest. Biogeosciences 9, 13–28.
35 doi:10.5194/bg-9-13-2012
- 36 1290 Xiao, J., Chen, J., Davis, K.J., Reichstein, M., 2012. Advances in upscaling of eddy covariance
37 measurements of carbon and water fluxes. Journal of Geophysical Research 117, G00J01.
38 doi:10.1029/2011JG001889
- 39 1293 Xiao, J., Zhuang, Q., Liang, E., Shao, X., McGuire, A.D., Moody, A., Kicklighter, D.W., Melillo, J.M.,
40 2009. Twentieth-century droughts and their impacts on terrestrial carbon cycling in
41 China. Earth Interactions 13, 1–31. doi:10.1175/2009EI275.1
- 42 1296 Zeeman, M.J., Hiller, R., Gilgen, A.K., Michna, P., Plüss, P., Buchmann, N., Eugster, W., 2010.
43 Management and climate impacts on net CO₂ fluxes and carbon budgets of three
44 grasslands along an elevational gradient in Switzerland. Agricultural and Forest
45

1
2
3
4 1299 Meteorology 150, 519–530. doi:10.1016/j.agrformet.2010.01.011
5 1300
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61

Tables

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

Country	Site	ID	Years	Latitude	Longitude	Elevation(m a.s.l.)	Geographical settings		Climate		
									Mean air temperature (°C)	Precipitation total (mm yr ⁻¹)	
France	Laqueuille	FRLaq1	2004-2010	45° 38' N	02° 44' E	1040			7.8	1072	Klumpp et al. (2011)
		FRLaq2	2004-2010								
Germany	Grillenburg	DEGri	2004-2008	50° 57' N	13° 30' E	375			8.5	946	Prescher et al. (2010)
Hungary	Bugac-Puszta	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)
	Amplero	ITAmp	2003-2007	41° 52' N	13° 38' E	884			9.4	781	Wohlfahrt et al. (2008)
Italy	Monte Bondone	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'Alinyà	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	NLCal	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)

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

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

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

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.

Parameters	Name	Unit	P_{temp} (Oensingen)	P_{perm} (Laqueuille)	P_{redef}	Description
Fractional C content of root structural dry matter ($f_{C,rt}$)	kg C kg ⁻¹ DM		0.5	0.43	0.43	
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_{nred})	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	
Root turnover rate at 20 °C (%)	d ⁻¹		0.05	0.048	0.048	They represent the leaf and root life-spans at a constant temperature, used to calculate the flow of plant residue.
Fraction of fibres in ingested ears (NDF_{ear})	-		0.8	0.742	0.742	
Fraction of fibres in ingested blades (NDF_{lam})	-		0.6	0.542	0.542	These parameters represent the proportion of fibre (NDF) in the ingested tissues (ear, lamina, sheath/stem).
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.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

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

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Digestible neutral detergent fibres of ears - age 1 (DNDF _{ears1})	kg digestible fibres kg ⁻¹ fibres	0.76	0.93	0.93
Digestible neutral detergent fibres of ears - age 2 (DNDF _{ears2})	kg digestible fibres kg ⁻¹ fibres	0.48	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
Digestible neutral detergent fibres of ears - age 4 (DNDF _{ears4})	kg digestible fibres kg ⁻¹ fibres	0.26	0.38	0.38
Light-saturated leaf photosynthetic rate for reproductive stage ($\varphi_{mco2/rep}$)	$\mu\text{mol C m}^{-2} \text{s}^{-1}$	22.6666	16.723	19.723
Light-saturated leaf photosynthetic rate for vegetative stage ($\varphi_{mco2/veg}$)	$\mu\text{mol C m}^{-2} \text{s}^{-1}$	15	11.099	13.099
Maximum specific leaf area (s _{lam})	$\text{m}^2 \text{ kg}^{-1}$	33.5	25	29
Temperature dependence factor of the soil respiration (m_H)	-	2	2	0.7

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

$$f(\mathbf{T}_a) = \begin{cases} \frac{(T_a - T_0)^q \cdot T'_0 \cdot (T'_0 - T_a)}{(T_{ref} - T_0)^q \cdot T'_0 \cdot (T'_0 - T_{ref})}, & T_0 \leq \mathbf{T}_a \leq T'_0 \\ 0 & \text{otherwise} \end{cases}$$

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

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

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

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)	$R^2 = \frac{\sum_{i=1}^n (\mathbf{P}_i - \bar{\mathbf{O}}) \cdot (\mathbf{O}_i - \bar{\mathbf{O}})}{\sqrt{\sum_{i=1}^n (\mathbf{P}_i - \bar{\mathbf{P}})^2 \cdot \sum_{i=1}^n (\mathbf{O}_i - \bar{\mathbf{O}})^2}}$	-	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)	$IA = 1 - \frac{\sum_{i=1}^n (\mathbf{P}_i - \bar{\mathbf{O}} + \mathbf{O}_i - \bar{\mathbf{O}})^2}{\sum_{i=1}^n (\mathbf{P}_i - \mathbf{O}_i)^2}$	-	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)	$RMSE = \sqrt{\frac{\sum_{i=1}^n (\mathbf{P}_i - \mathbf{O}_i)^2}{n}}$	unit of the variable	0 (optimum) to positive infinity: the smaller RMSE, the better the model performance	-	-
MB, mean bias (Addiscott and Whitmore, 1987)	$MB = \frac{\sum_{i=1}^n (\mathbf{P}_i - \mathbf{O}_i)}{n}$	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)	$ME = 1 - \frac{\sum_{i=1}^n (\mathbf{P}_i - \mathbf{O}_i)^2}{\sum_{i=1}^n (\mathbf{O}_i - \bar{\mathbf{O}})^2}$	-	negative infinity to 1 (optimum); the closer the values are to 1, the better the model	>0.5	Moriasi 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 _R					
	BIAS g C week ⁻¹ .m ⁻²	RMSE g C week ⁻¹ .m ⁻²	IA	ME	R ²	BIAS g C week ⁻¹ .m ⁻²	RMSE g C week ⁻¹ .m ⁻²	IA	ME	R ²	BIAS mm week ⁻¹	RMSE mm week ⁻¹	IA	ME	R ²			
CHOel	-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			
FRIq1	-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			
FRIq2	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			
NLCal	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			
NEE																		
Site ID	BIAS g C week ⁻¹ .m ⁻²	RMSE g C week ⁻¹ .m ⁻²	IA	ME	R ²	BIAS	RMSE	IA	ME	R ²	BIAS % ^a	RMSE % ^a	IA	ME	R ²			
	CHOel	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			

Comment citer ce document :

Ma, S., Lardy, R., Graux, A.-L., 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

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

	FRIq1	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
FRIq2	-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	
PTM12	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	
NLCal	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	

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

Figures:

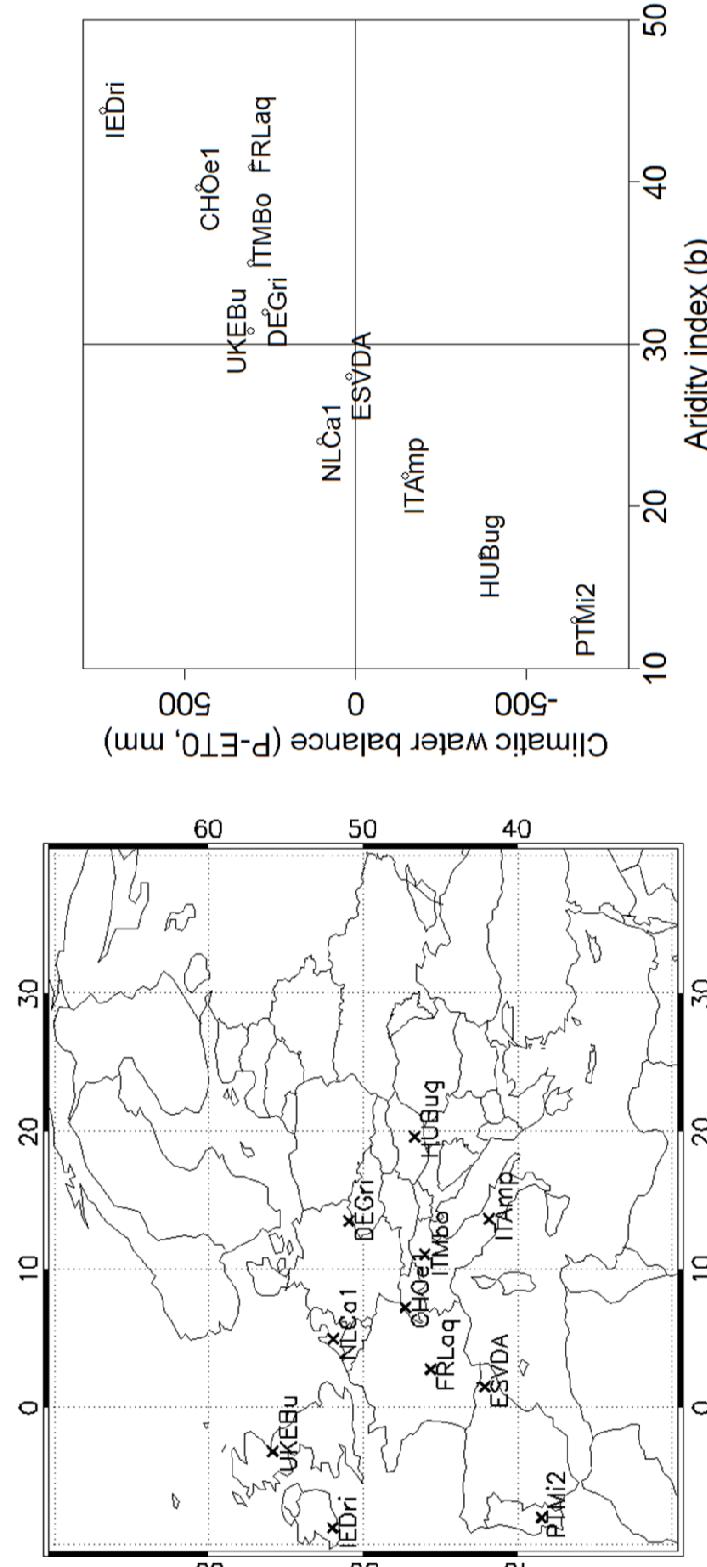


Fig. 1. Geographic location (left) and classification (right) of grassland sites (ID as in Table 1) with respect to two indices (climatic water balance and De Martonne-Gottmann aridity index) of water availability. For the aridity index b, (De Martonne, E, 1942), the following range limits discriminate 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).

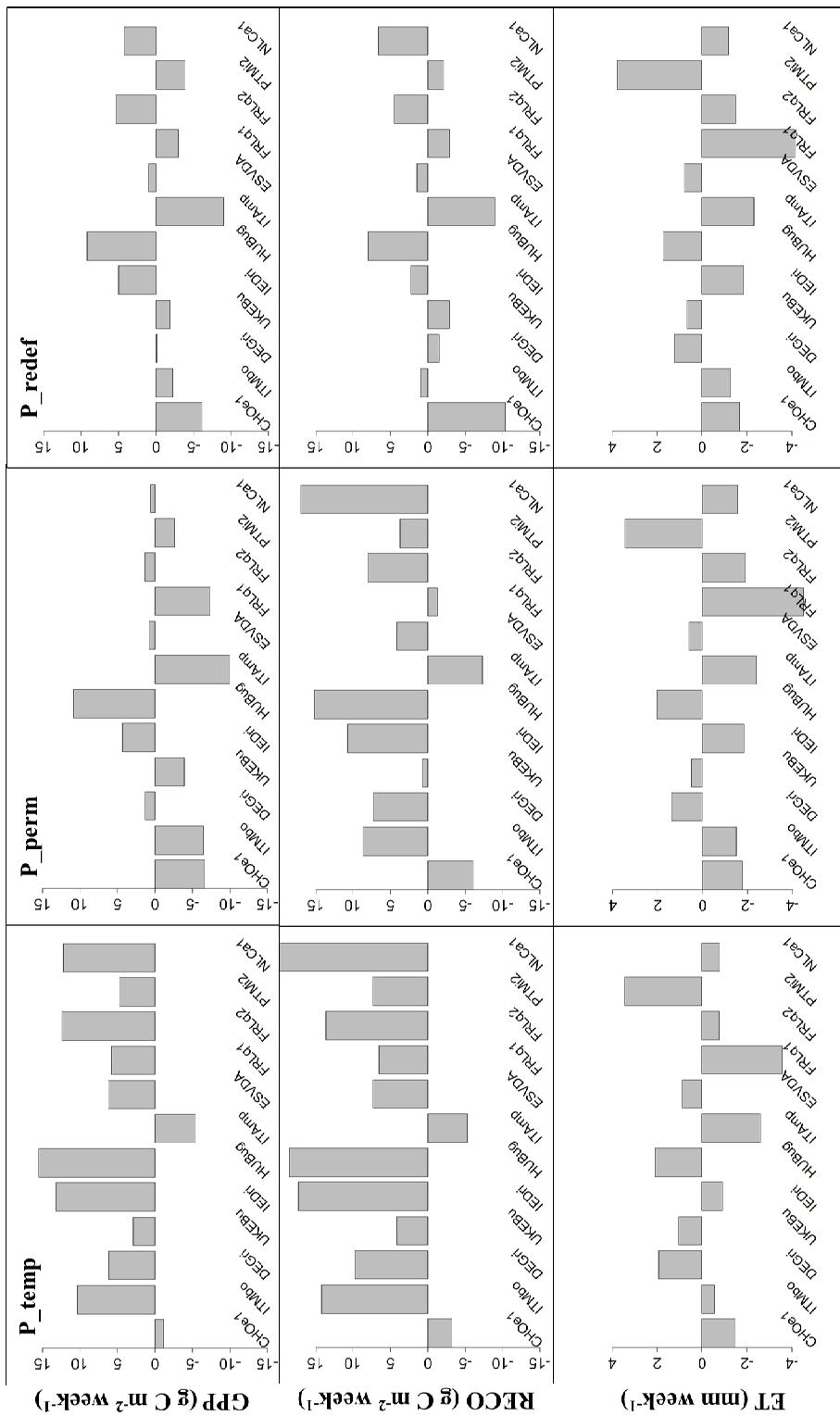
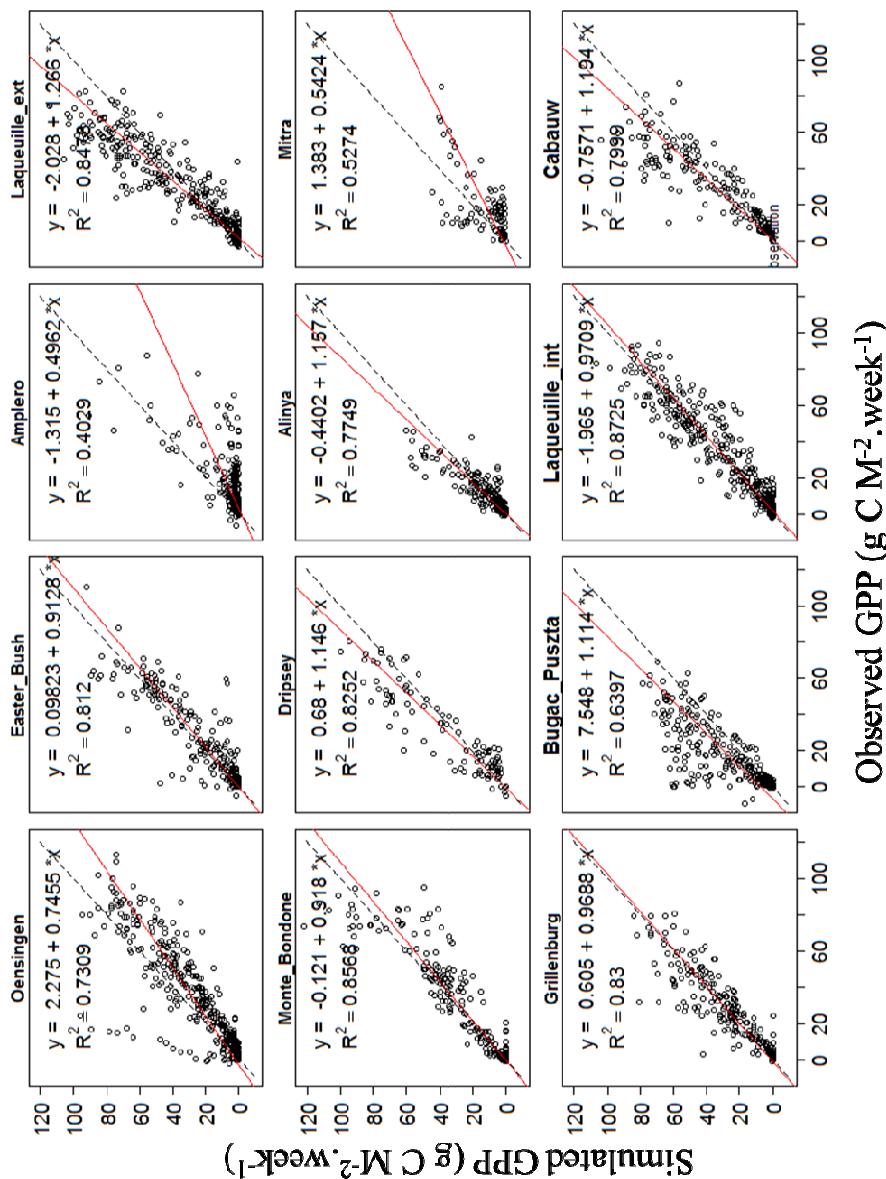


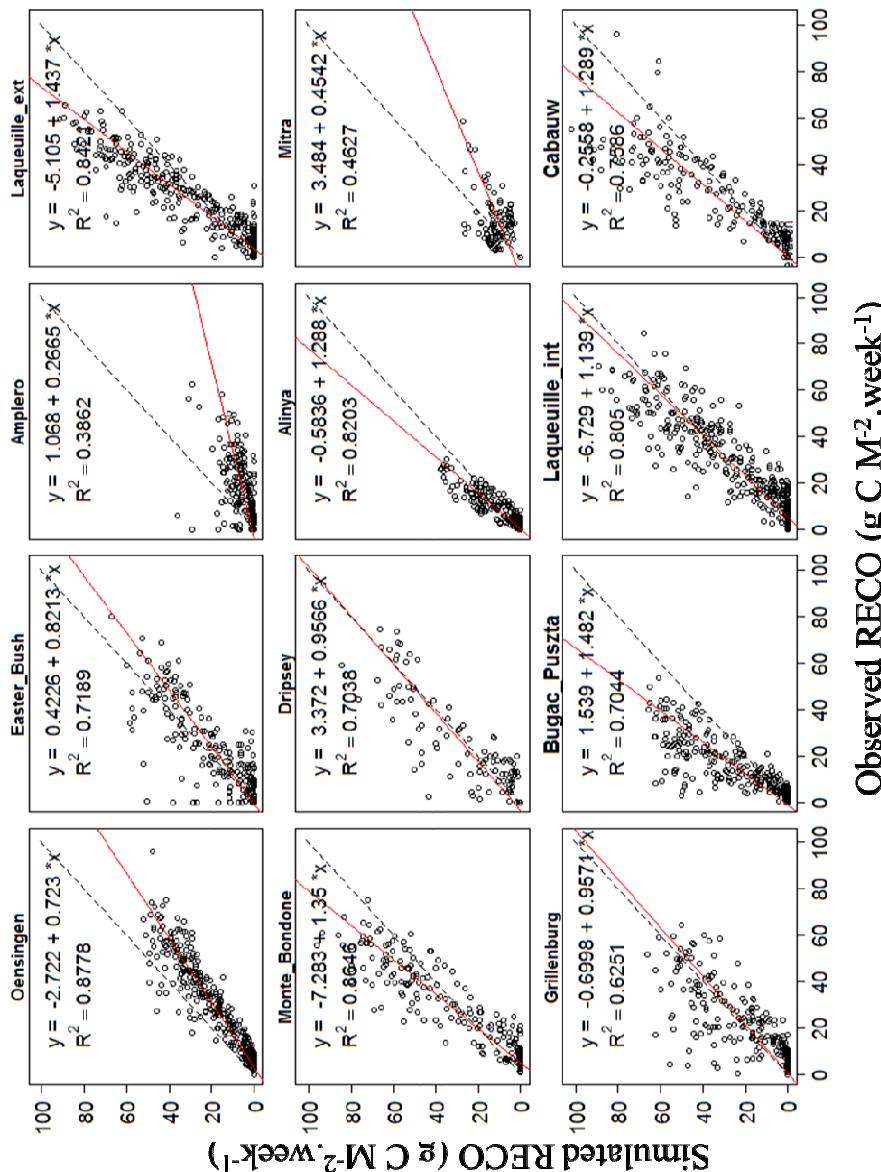
Fig 2. The mean bias of weekly values of GPP, RECO ($\text{g C m}^{-2} \text{ week}^{-1}$) and ET (mm week^{-1}), using three sets of parameter values: for temporary grasslands as established at Oensingen, Switzerland (P_{temp} , left), for permanent grasslands as established at Laqueuille, France (P_{perm} , middle), and the common set established in this study (P_{redef} , right).

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

**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.

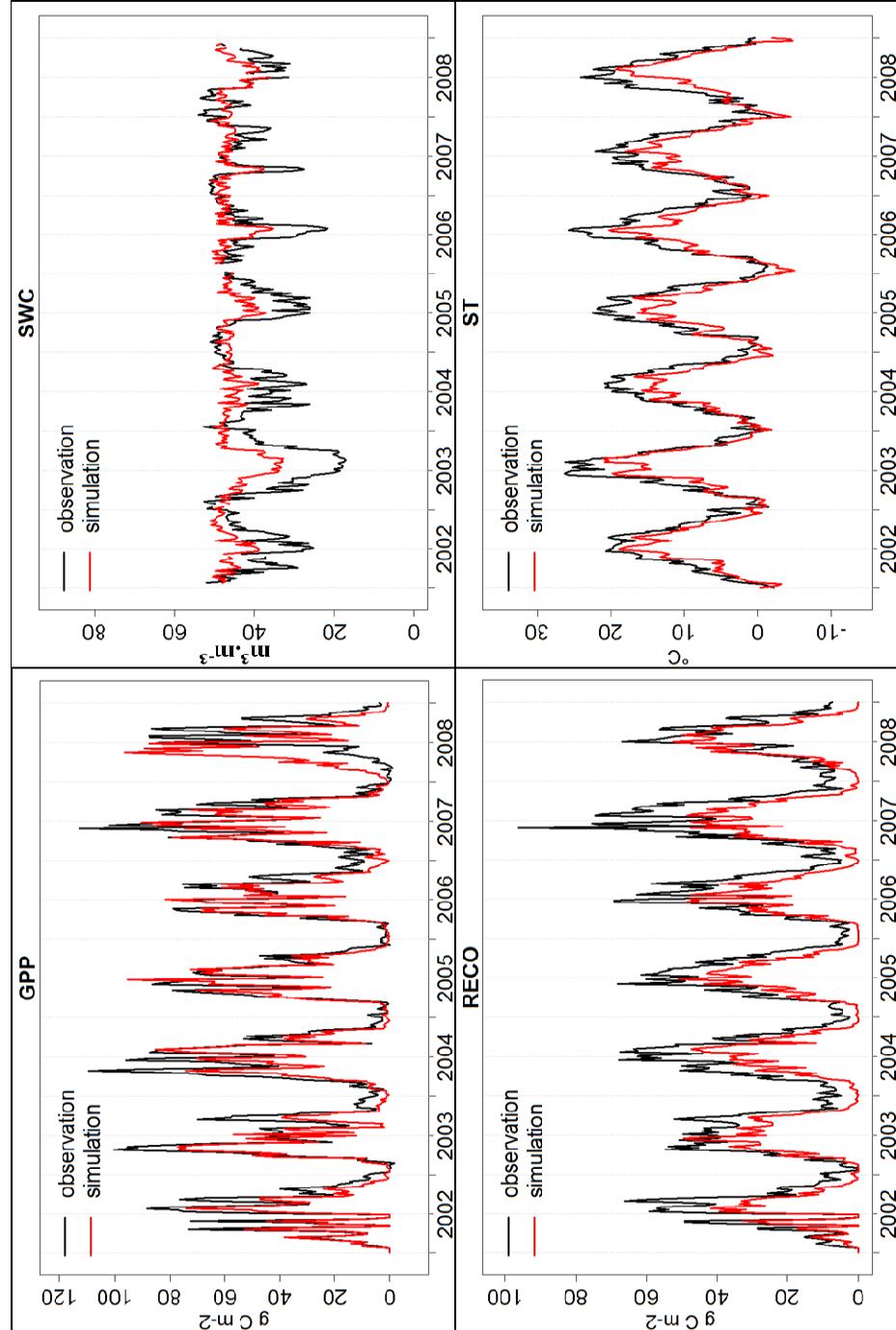


Fig. 5. The variability of simulated GPP, RECO, soil temperature (ST) and soil water content (SWC) against the observed data for Oensingen (Switzerland) weekly values.

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

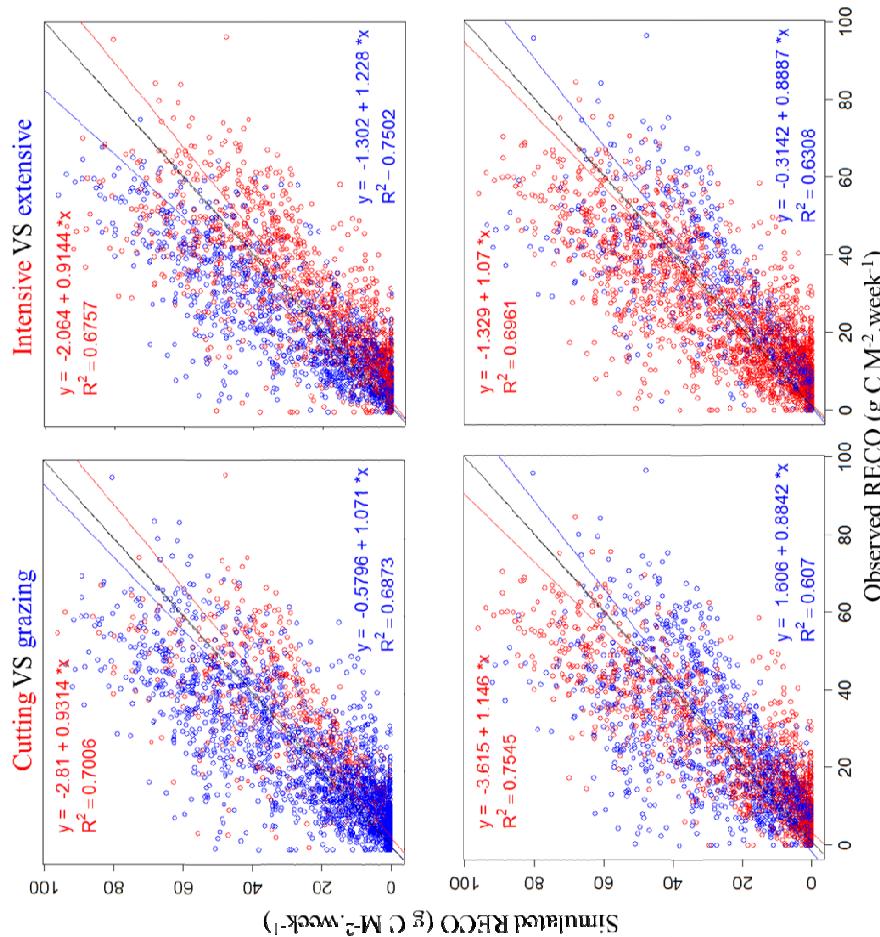


Fig. 6. Scatter plots of simulated with the redefined parameters versus measured RECO values (g C M⁻².week⁻¹) according to site characteristics and management practices. The goodness-of-fit R² is the coefficient of determination of the regression equation.

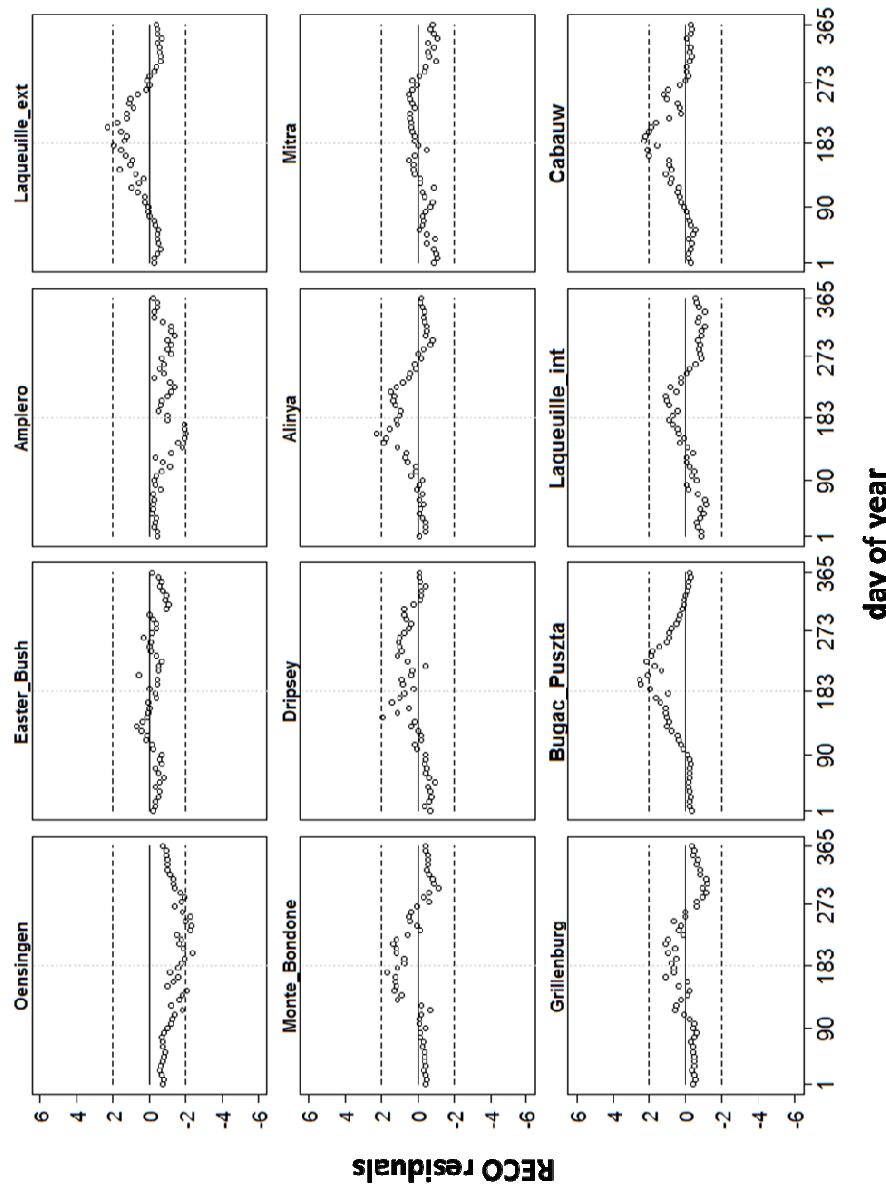


Fig. 7. Normalized residuals of RECO plotted versus day of year for each grassland site. Each point is the average of residuals for all years divided by the standard deviation. Horizontal lines represent the 95% confidence limits.

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

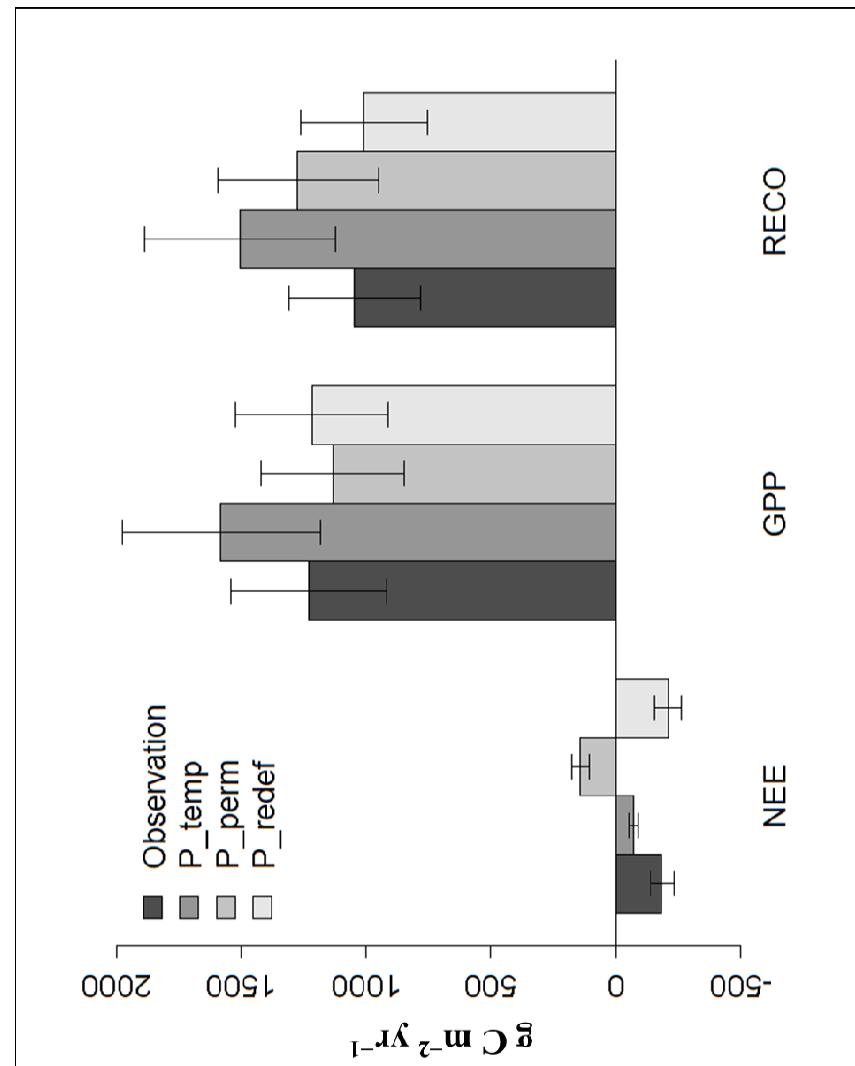


Fig. 8. Comparison of observed and simulated carbon fluxes (NEE, GPP, RECO; g C m⁻² yr⁻¹) with different parameter values (default for Oensingen (P_temp) and Laqueuille (P_perm), and new parameter values (P_redef)). The values are averaged across all grassland sites.

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

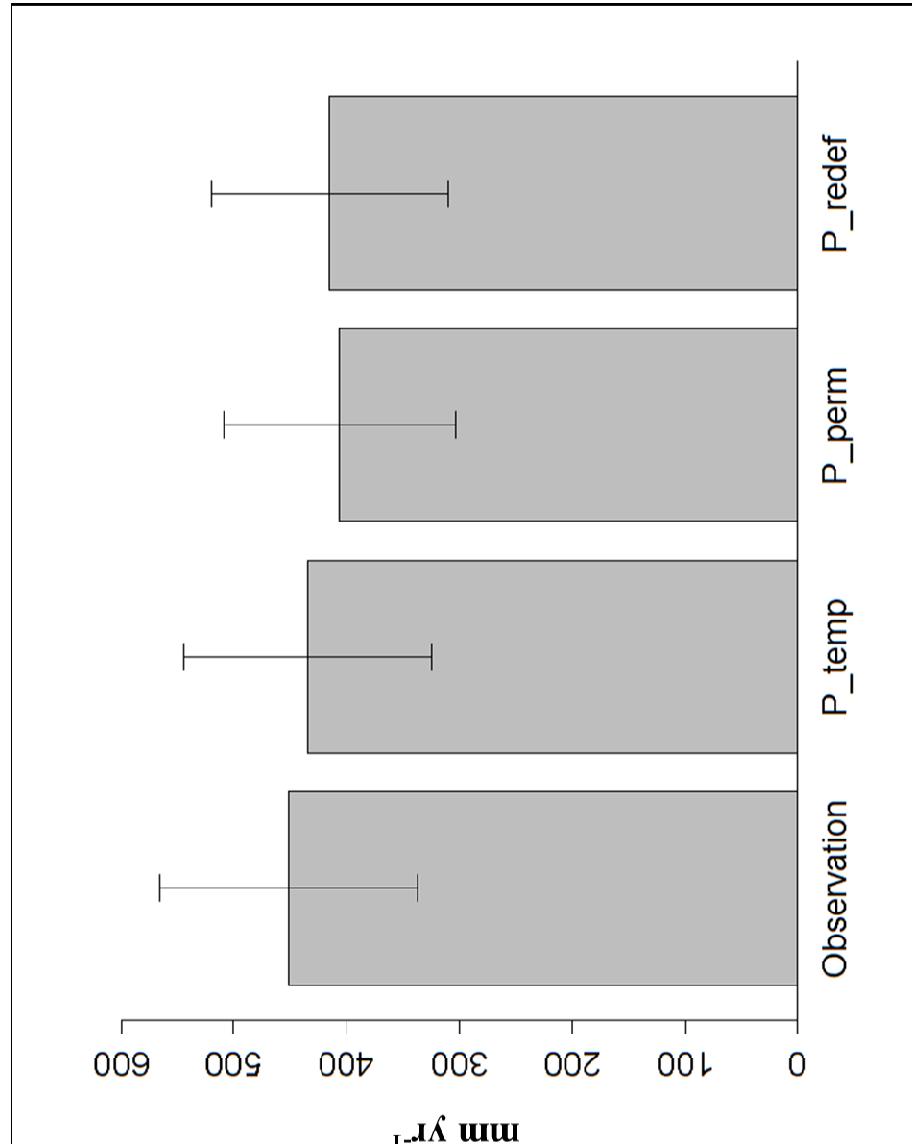


Fig. 9. Comparison of observed and simulated water fluxes (mm yr^{-1}) with different parameter values (default for Oensingen (P_temp) and Laqueuille (P_perm), and new parameter values (P_redef)). The values are averaged across all grassland sites.

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

Appendix G: support figures

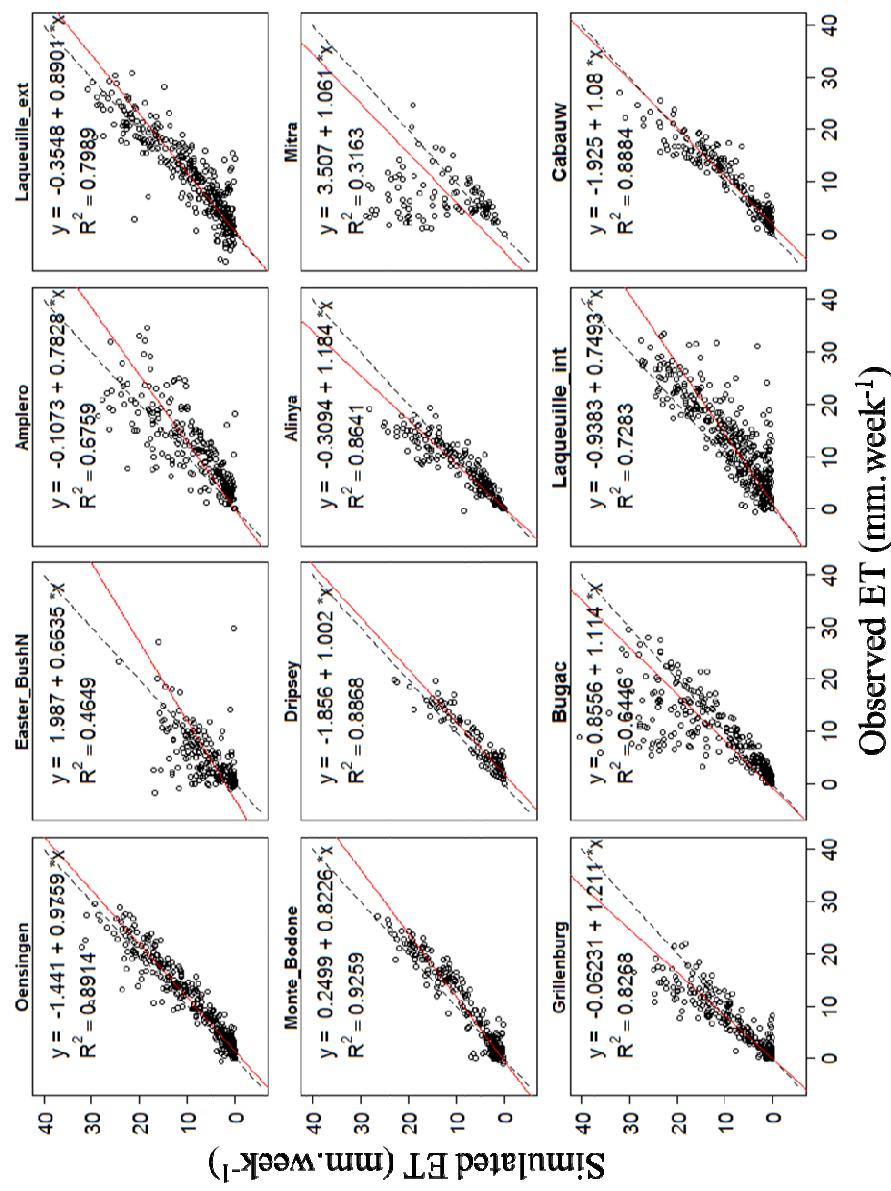


Fig. A1. Scatter plots of simulated versus measured ET weekly values.

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

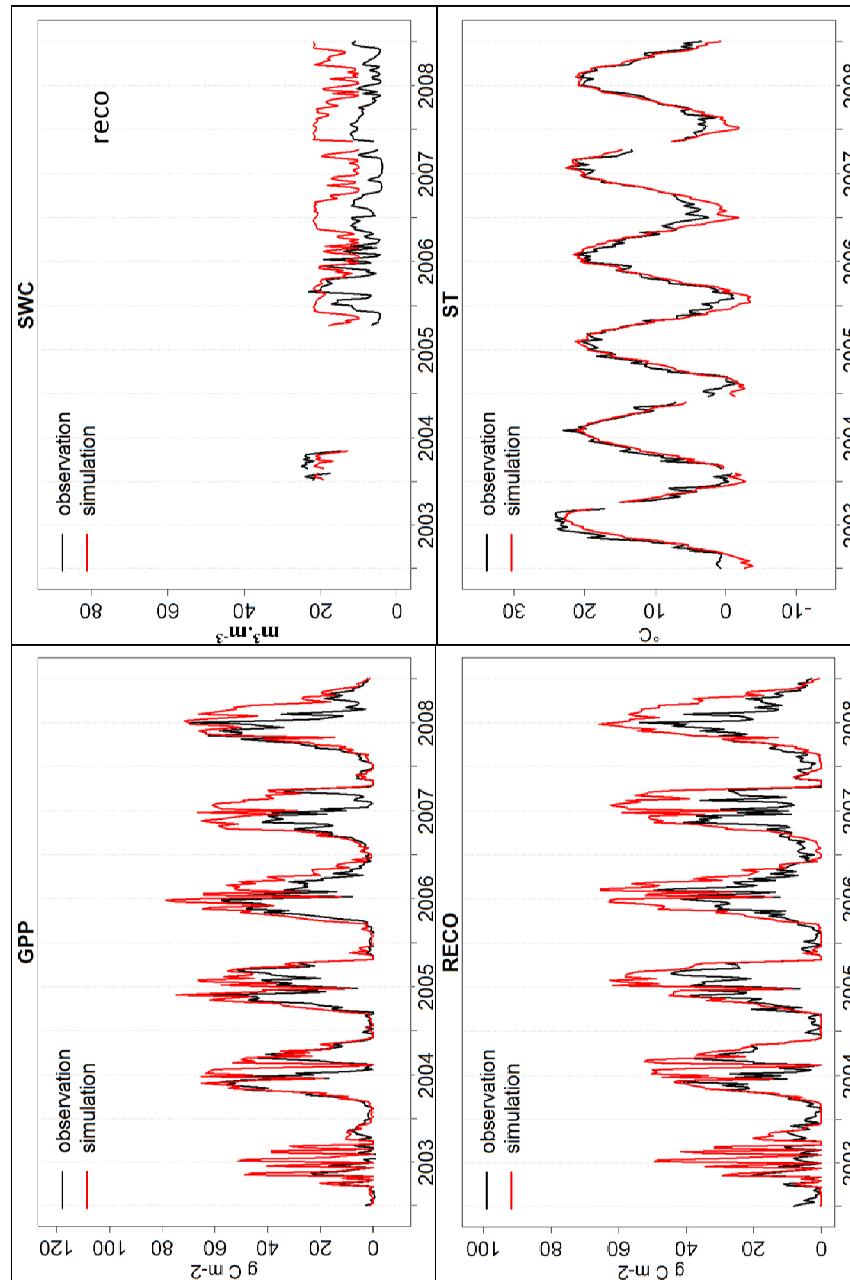


Fig. A2. The variability of simulated GPP, RECO, soil temperature (ST) and soil water content (SWC) against the observed data for Bugac-Puszta (Hungary) weekly values.

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

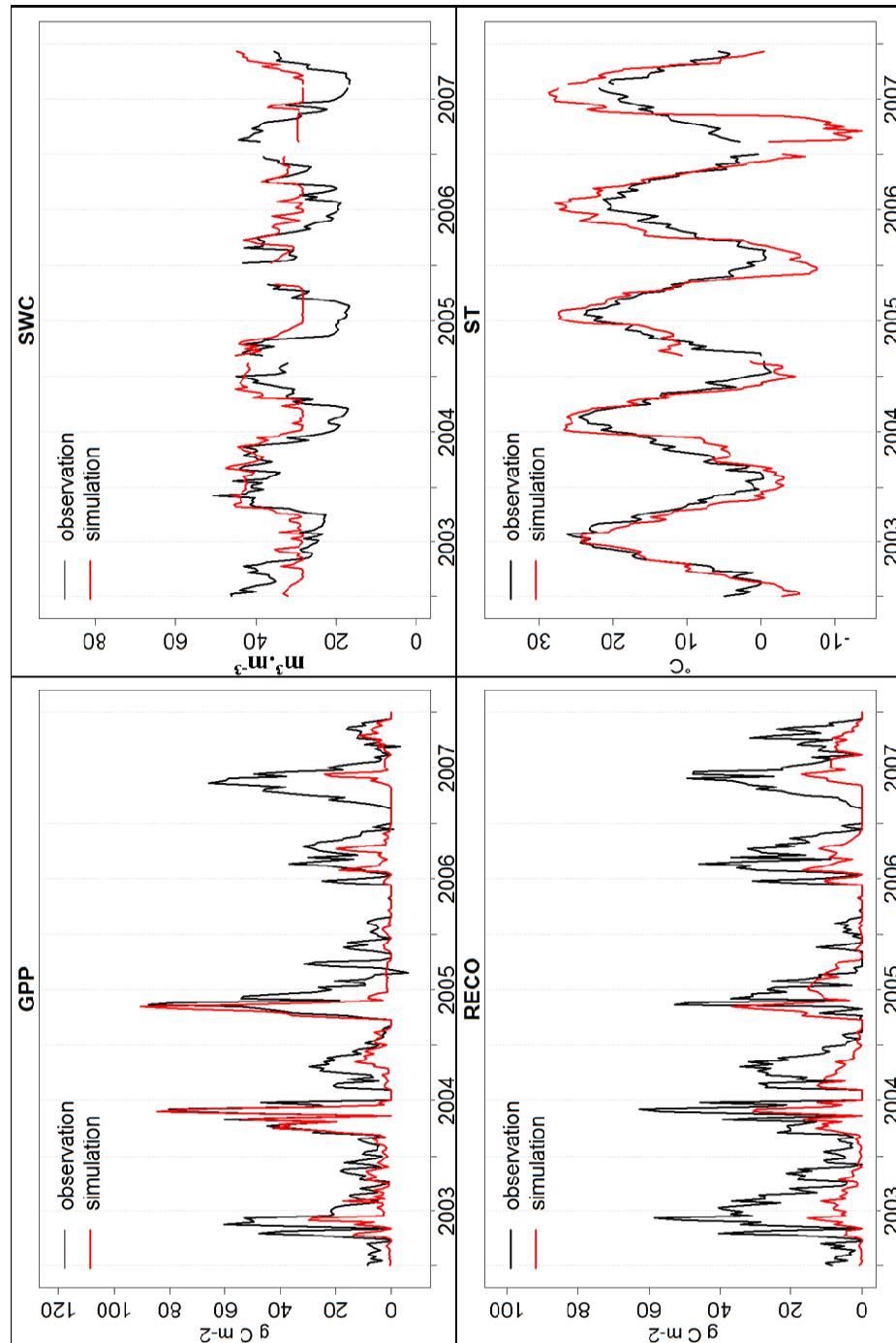
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

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

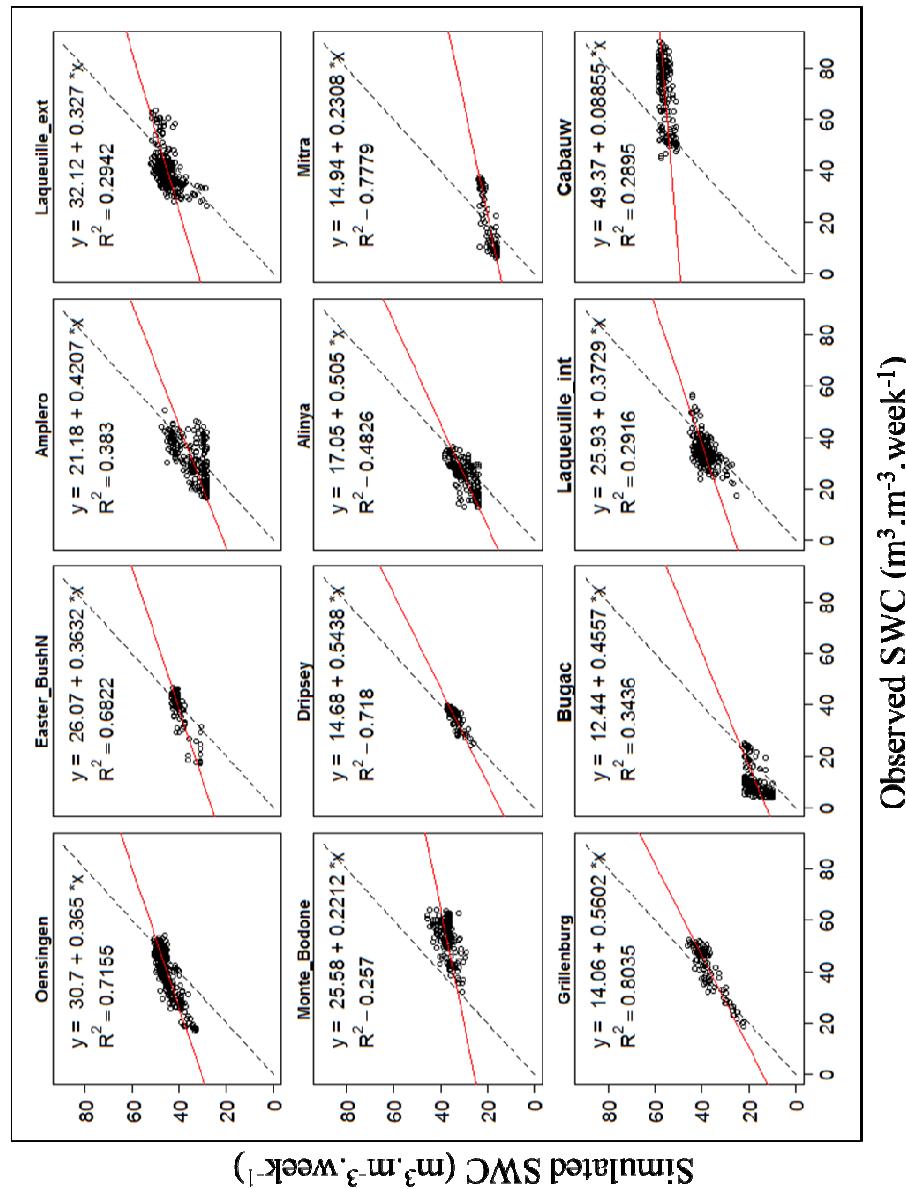


Fig. A4. Scatter plots of simulated versus measured soil water content in the top 10 centimetres.

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

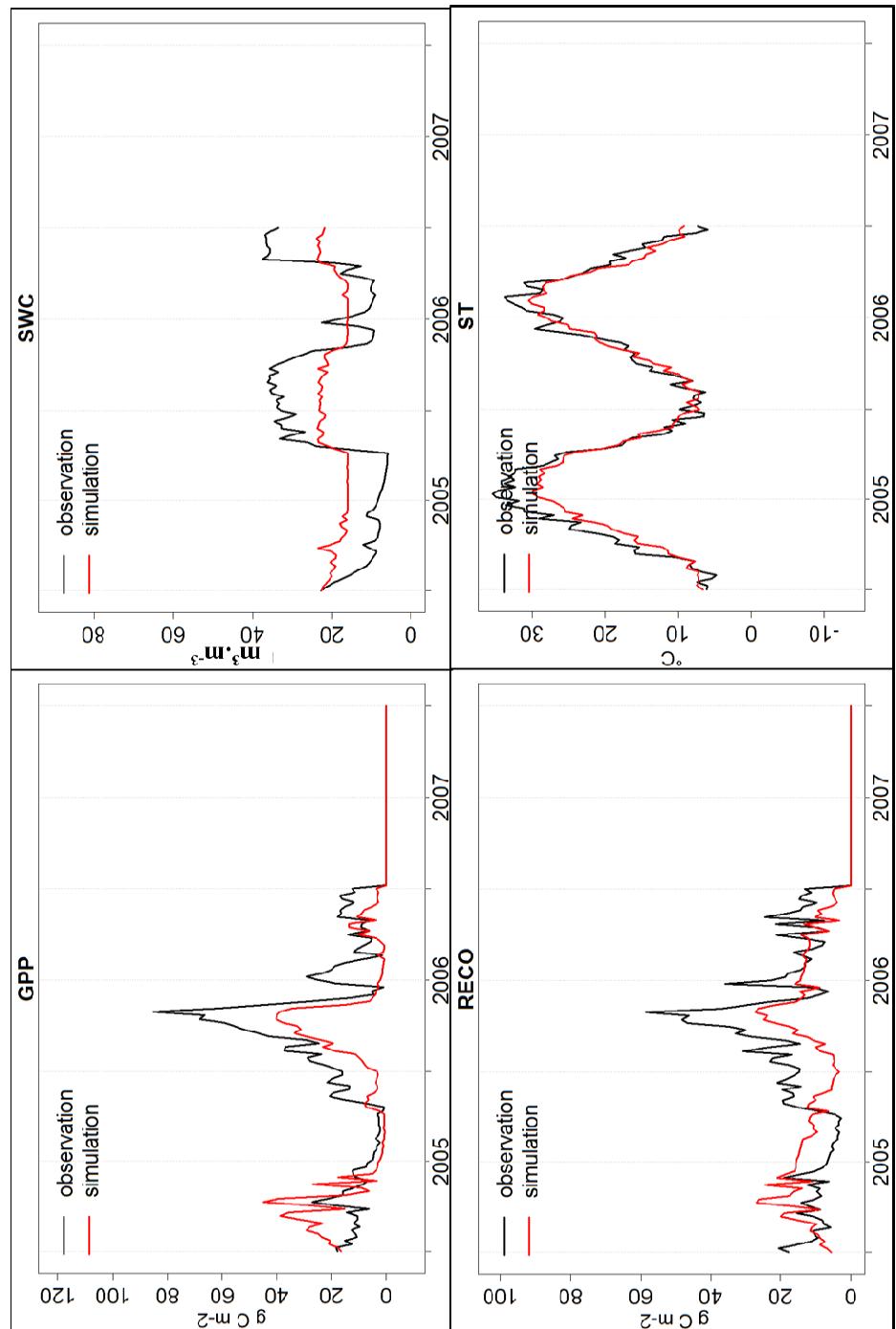


Fig. A5. The variability of simulated GPP, RECO, soil temperature (ST) and soil water content (SWC) against the observed data for Mitra (Portugal) weekly values.

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

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

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