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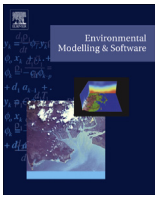

Regional-scale analysis of carbon and water cycles on managed grassland systems[☆]

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ABSTRACT

Predicting regional and global carbon (C) and water dynamics on grasslands has become of major interest, as grasslands are one of the most widespread vegetation types worldwide, providing a number of ecosystem services (such as forage production and C storage). The present study is a contribution to a regional-scale analysis of the C and water cycles on managed grasslands. The mechanistic biogeochemical model PaSim (Pasture Simulation model) was evaluated at 12 grassland sites in Europe. A new parameterization was obtained on a common set of eco-physiological parameters, which represented an improvement of previous parameterization schemes (essentially obtained via calibration at specific sites). We found that C and water fluxes estimated with the parameter set are in good agreement with observations. The model with the new parameters estimated that European grassland are a sink of C with 213 g C m^{-2} yr^{-1}, which is close to the observed net ecosystem exchange (NEE) flux of the studied sites (185 g C m^{-2} yr^{-1} on average). The estimated yearly average gross primary productivity (GPP) and ecosystem respiration (RECO) for all of the study sites are 1220 and 1006 g C m^{-2} yr^{-1}, respectively, in agreement with observed average GPP (1230 g C m^{-2} yr^{-1}) and RECO (1046 g C m^{-2} yr^{-1}). For both variables aggregated on a weekly basis, the root mean square error (RMSE) was ~5–16 g C $week^{-1}$ across the study sites, while the goodness of fit (R^2) was ~0.4–0.9. For evapotranspiration (ET), the average value of simulated ET (415 mm yr^{-1}) for all sites and years is close to the average value of the observed ET (451 mm yr^{-1}) by flux towers (on a weekly basis, RMSE~2–8 mm $week^{-1}$; $R^2 = 0.3–0.9$). However, further model development is needed to better represent soil water dynamics under dry conditions and soil temperature in winter. A quantification of the uncertainties introduced by spatially generalized parameter values in C and water exchange estimates is also necessary. In addition, some uncertainties in the input management data call for the need to improve the quality of the observational system.

Software availability

Name of Software: Pasture Simulation model (PaSim)
Developer: INRA, UR0874 initiative; contact: Raphaël Martin
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Availability: On request to the authors
Cost: free for no-profit use
Program language: Fortran

1. Introduction

Accurate quantification of ecosystem carbon (C) and water fluxes over regions, continents, or the globe is essential for understanding the feedbacks between the terrestrial biosphere and the atmosphere in the context of global change and climate policy-making (Xiao et al., 2012; Ciais et al., 2013). In the last decades, significant progresses have been made in quantifying regional to

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

Grasslands are a widespread vegetation type worldwide, covering nearly one-fifth of the world's land surface (24 million km^2) (Suttie et al., 2005) and playing a significant role in the global C cycle (Scurlock and Hall, 1998; Ciais et al., 2010). At global scale, grasslands were estimated to be a net C sink of about 0.5 Pg C per year (Scurlock and Hall, 1998), but with high spatial heterogeneity and considerable uncertainty on the estimate of C exchange. Janssens et al. (2005) estimated that grasslands provide a C sink of 66 ± 90 g C m^{-2} yr^{-1} over Europe. From an extensive network of flux towers, Schulze et al. (2009) inferred a net C sink: net biome production (NBP) in European grasslands of 57 ± 34 g C m^{-2} yr^{-1}. However, grassland ecosystems are the most uncertain components of the Europe-wide C balance in comparison to forests and croplands because only few data and grassland-specific models are available (Ciais et al., 2010). As a consequence, it is urgent to improve and evaluate grassland models based on recently-available eddy flux data.

Over the last decades, grassland models were developed with different research foci. 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 biophysical, but also dairy management options (Johnson et al., 2008). Several integrated or whole farm system models were also available to simulate the biogeochemical processes and also include decision support system, such as Whole Farm Model (Bright et al., 2000), GP-FARM (Ascough et al., 2007), Integrated Farm System Model (http://www.ars.usda.gov/Main/docs.htm?docid=8519) and FASSET (Chirinda et al., 2011). An overview of the state of the art and the developments needed for process-based modelling of grazed agricultural systems were addressed by Snow et al. (2014).

Recently, attempts have also been made to introduce management options into global dynamic vegetation and crop models in order to extend functionalities for grasslands on regional and global scales. Biome and global dynamic vegetation models such as LPJmL (Bondeau et al., 2007), Biome-BGC (Hidy et al., 2012), ORCHIDEE (Krinner et al., 2005) and CARAIB (Warnant et al., 1994) were improved with mowing and grazing options. At the same time, widely used crop models, such as STICS (Brisson et al., 2003; Ruget et al., 2009), EPIC (Williams et al., 1989), CropSyst (Stöckle et al., 2003), DNDC (Rafique et al., 2011; Wang et al., 2012), DSSAT (Giraldo et al., 1999) and the APSIM platform (Holzworth et al., 2014) have also been adapted to simulate grasslands. These efforts have made great contributions to the overall development of grassland models (yet with a different detail in representing processes). However, model evaluation was limited in scope to specific goals (e.g. not all grassland models simulate biogeochemical cycles). A detailed evaluation of model performance against observational flux data from a variety of grassland sites is therefore desirable. In particular, for a process-based model representing in detail the mechanisms driving the functioning of grassland systems, evaluation is needed with extended datasets, which include different grassland observational sites with a diversity of climatic, management and soil conditions.

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

A monitoring network consisting of a total of 12 grassland sites was established in 2002 and eddy-covariance flux measurements were made on this network within the European projects of the 5th, 6th and 7th framework programs, such as GREENGRASS (Soussana et al., 2007b), CARBOMONT (Bahn et al., 2008; Wohlfahrt et al., 2008), CarboEurope (Gilmanov et al., 2010) and CARBO-Extreme (Reichstein et al., 2013). This dataset provides a good opportunity to evaluate grassland model performances because these sites cover a variety of grassland types with contrasting management practices and representing different climate conditions.

The present study assesses the ability of PaSim to reproduce C and water fluxes of a number of European long-term eddy flux measurement sites. To do so, three sets of eco-physiological vegetation parameters (i.e. from permanent grassland, sown grassland, and an adjusted set, which is the calibrated parameter values based on flux measurements data and their plausible ranges) were applied in order to test whether a common set of vegetation parameters is appropriate to represent model outputs at European scale (regardless of the possible physiological dissimilarities among grasslands species in different places in Europe). Model calibration was not applied separately to each observational site. This did not make it possible to explore the spatial variability of model parameters. Testing such a scenario appeared beyond the scope of this paper since it implied too strong a deviation from the initial hypothesis of this regional study. Rather, we calibrated the model simultaneously on all datasets to find parameter values that would be applicable at regional scale. Multi-site calibration can be characterized by lower uncertainty than site-specific calibration, because more data are

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