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Modelling heat, water and carbon fluxes in mown grassland under multi-objective and multi-criteria constraints

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ABSTRACT

A Monte Carlo-based calibration and uncertainty assessment was performed for heat, water and carbon (C) fluxes, simulated by a soil-plant-atmosphere system model (CoupModel), in mown grassland. Impact of different multi-objective and multi-criteria constraints was investigated on model performance and parameter behaviour. Good agreements between hourly modelled and measurement data were obtained for latent and sensible heat fluxes ($R^2 = 0.61$, $ME = 0.48$ MJ m^{-2} day^{-1}), soil water contents ($R^2 = 0.68$, $ME = 0.34\%$) and carbon-dioxide flux ($R^2 = 0.60$, $ME = -0.18$ g C m^{-2} day^{-1}). Multi-objective and multi-criteria constraints were efficient in parameter conditioning, reducing simulation uncertainty and identifying critical parameters. Enforcing multi-constraints separately on heat, water and C processes resulted in the highest model improvement for that specific process, including some improvement too for other processes. Imposing multi-constraints on all groups of variables, associated with heat, water and C fluxes together, resulted in general effective parameters conditioning and model improvement.

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Software availability

Name of software: CoupModel 5.0
Developer and contact address: Division of Land and Water Resources, Department of Civil and Environmental Engineering, Royal Institute of Technology, SE-100 44 Stockholm, Sweden Tel. and fax: +46-8-790-8286; +46-8-411-07-75
WWW: https://www.coupmodel.com/
E-mail: pej@kth.se
Year of first available: 2000
Program language: Visual C++
Software required: Windows 95-10
Availability and cost: An executable program can be downloaded at the above sites free of charge, source code available on request

1. Introduction

Grassland is one of the most widespread terrestrial ecosystems, covering approximately 40% of the global land surface, containing the largest share (39%) of terrestrial soil carbon (C) (about 580 Gt C), and plays a significant role in the global C cycle (White et al., 2000; Wang and Fang, 2009). High sequestration potential of atmospheric carbon dioxide (CO_2) by grassland ecosystems has attracted considerable attention from scientists and policy makers in recent years, with a global grassland soil organic carbon (SOC) sequestration potential of 0.2–0.8 Gt CO_2 yr^{-1} by 2030 (IPCC, 2000; Smith et al., 2008). Irrespective of climate, soil and grass species (C_3 and C_4), different grassland management regimes, such as mowing and grazing including fertilization, and their intensities mostly determine source and sink activity of grassland ecosystems (Soussana et al., 2010; McSherry and Ritchie, 2013). Positive grassland C sequestration potential has been found under light-to-moderate grazing, mainly favoured by higher root biomass, faster shoot and root turnover, more diverse plant species, improved soil fertility and lower net C export (Allard et al., 2007; Oates and Jackson, 2014). Negative impacts of overgrazing have also been reported (Li et al., 2008). Mown grassland can also sequester C depending on

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the intensity of cutting (Ammann et al., 2007), though temperate European grasslands generally have smaller C storage potential under mowing than grazing (Soussana et al., 2010; Senapati et al., 2014). However, different ecological processes relating to the C cycle are still poorly understood in grassland ecosystems (McSherry and Ritchie, 2013). Different grassland management regimes are also expected to influence energy and water fluxes along with C, as different heat (radiation, surface and soil heat fluxes, soil temperature), water (soil water content, evapotranspiration) and C processes (photosynthesis, C allocation, plant and soil respiration, net C uptake) are inter-linked (Wu et al., 2012). Therefore, simultaneous investigation of C, heat and water fluxes together can improve our understanding better on grassland ecosystems (Ciais et al., 2013).

A better understanding of C fluxes along with heat and water fluxes in grassland ecosystems requires not only field experiment, but also process-based, simulation models. Different information collected from various sources, representing different components of the ecosystem, can be combined in models to understand the whole ecosystem (Smith and Smith, 2007). Process-based models are designed with the objective of explicitly representing the actual systems, providing a feasible way to predict long-term responses of ecosystems to external forces such as climate or management. In the last few decades, many process-based, soil-plant-atmosphere system models have been developed, describing different biotic and abiotic processes with different levels of complexity, for example CENTURY (Parton, 1996), DNDC (Li et al., 2000), Pasim (Riedo et al., 1998), CoupModel (Jansson and Moon, 2001) etc. Although there is a need for simplicity in models, basic ecosystem processes should be simulated in sufficient detail (Blagodatsky and Smith, 2012). Again, model simulations at higher time resolution could help to understand ecosystem processes more precisely. In the present study the CoupModel, which is a process-based coupled heat and mass transfer model for soil-plant-atmosphere systems, was used for simulation of heat, water and carbon fluxes in mown grassland system. The CoupModel was selected for the following reasons: (a) the model is designed for a wide range of ecosystems, facilitating its application in different ecosystems including grassland ecosystems, (b) CoupModel simulates different processes related with C, heat and water cycles in sufficient detail and at high temporal resolution (e.g., hourly), which are necessary for modelling high frequency measured variables (e.g., Eddy-covariance data), (c) user can easily select different sub-modules, equations and complexity according to the modelling objectives, and (d) the model supports detailed model parameterization and uncertainty based model calibration within its modelling framework (Jansson, 2012; Jansson and Karlberg, 2013). Different model inter-comparison studies reported CoupModel performance towards the better model groups in simulation of C and water dynamics in forest ecosystem (van Oijen et al., 2011; Palosuo et al., 2012). Recently, the model is being used for model comparison (CoupModel, JULES and LPJ-GUESS) for both site applications as well as transects studies in regional scale within European Union (ExpeEr ecosystem research project, WP9: http://michaelmi.nateko.lu.se/). Recent studies demonstrated that the CoupModel has the potential to successfully simulate different ecosystem processes including C, water and heat fluxes, at high temporal resolution over long time periods in forest ecosystems (Wu et al., 2011a, 2012). However, before using a model and experimental data to predict behaviour for non-investigated new environments, the model needs to be tested carefully on both model structure and parameter uncertainty. The CoupModel has limited application in grasslands with efforts to estimate parameter distributions from experimental field investigations (Conrad and Fohrer, 2009; Wang et al., 2013). In the present study, the CoupModel was used to simulate C, water and heat fluxes at a 1 h time step in a well-established temperate grassland experiment under a mowing management system, with the objective of evaluating model performance and analysing to what extent parameter distributions could be estimated using high frequency measurements.

Uncertainties in model inputs, parameters, structure and evaluation data are unavoidable, resulting in uncertainty in model simulations (Beven and Binley, 2014). Uncertainty based model calibration can help in quantifying unknown uncertainties, and also model improvement, by reducing parameters as well as total simulation uncertainty. Although, there are many studies in modelling C, water and heat fluxes in grassland ecosystems (Chang et al., 2013; Kirschbaum et al., 2015; Ma et al., 2015), detailed uncertainty based model parameterization using high frequency measurements is limited in modelling heat, water and C cycle together in grassland ecosystems (Ben Touhami and Bellocchi, 2015; Sándor et al., 2016). Among different methods available for uncertainty estimation and calibration of complex environmental system models, the generalized likelihood uncertainty estimation (GLUE) method is now widely gaining popularity and is being used in a range of complex ecosystem studies including hydrology (Efstratiadis and Koutsoyiannis, 2010), CO_2 and heat flux (Franks et al., 1999; Mitchell et al., 2009), soil C (Juston et al., 2010) and nitrogen (Conrad and Fohrer, 2009). The GLUE methodology was developed by Beven and Binley (1992) as a general strategy for model uncertainty estimation and calibration based on the equifinality thesis. The GLUE method does not search for a single optimal parameter set, instead it investigates sets of parameter values that would produce equally good simulations, called equifinality (Beven, 2006). The GLUE framework was chosen for this study for its conceptual simplicity and flexibility. GLUE is based on Monte Carlo simulation, using different parameter sets chosen randomly from the specified ranges for each parameter. The performance of each model run is evaluated by multiple performance or likelihood measures, based on comparison of simulated versus observed outputs. Each run is classified as behavioural or non-behavioural by setting an acceptance threshold limit or acceptance criteria. In the GLUE framework, selection of likelihood measures and limit of acceptability are important, but are chosen subjectively unless the user has strong assumptions about the nature of the error model, which is difficult to justify in real world complex ecosystem studies (Beven, 2006; Beven et al., 2008). However, various studies have demonstrated different model sensitivities to different acceptable criteria (Choi and Beven, 2007; Wu et al., 2013). Different multi-objective but independent measured variables, which describe different characteristics of a system, are crucial for parameter conditioning and model improvement, as more information about a system is believed to reduce total simulation uncertainty (Franks et al., 1999; Schulz et al., 2001; Prihodko et al., 2008). Although, recently more and more detailed data sets are becoming available in ecosystem studies (Chang et al., 2013; Senapati et al., 2014; Ma et al., 2015; Sándor et al., 2016), there is no consensus on how to use such data sets to test the model performance, or improve our understanding and model performance for different ecosystem processes. In the present study, we presented a Monte Carlo-based calibration and uncertainty assessment procedure within GLUE framework by implementing different multi-objective and multi-criteria constraints on heat, water and C processes in grassland ecosystem, taking CoupModel as an example of a process-based, soil-plant-atmosphere system model, with the aims of exploring the influence of multi-objective variables and associated multiple criteria on model performance, reducing and estimating total simulation uncertainty, and defining new improved parameter distributions to represent grassland ecosystems.

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