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Multi-model simulation of soil temperature, soil water content and biomass in Euro-Mediterranean grasslands: Uncertainties and ensemble performance

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ABSTRACT

This study presents results from a major grassland model intercomparison exercise, and highlights the main challenges faced in the implementation of a multi-model ensemble prediction system in grasslands. Nine, independently developed simulation models linking climate, soil, vegetation and management to grassland biogeochemical cycles and production were compared in a simulation of soil water content (SWC) and soil temperature (ST) in the topsoil, and of biomass production. The results were assessed against SWC and ST data from five observational grassland sites representing a range of conditions – Grillenburg in Germany, Laqueuille in France with both extensive and intensive management, Monte Bondone in Italy and Oensingen in Switzerland – and against yield measurements from the same sites and other experimental grassland sites in Europe and Israel. We present a comparison of model estimates from individual models to the multi-model ensemble (represented by multi-model median: MMM). With calibration (seven out of nine models), the performances were acceptable for weekly-aggregated ST ($R^2 > 0.7$ with individual models and >0.8–0.9 with MMM), but less satisfactory with SWC ($R^2 < 0.6$ with individual models and $< \sim 0.5$ with MMM) and biomass ($R^2 < \sim 0.3$ with both individual models and MMM). With individual models, maximum biases of about −5 °C for ST, −0.3 $m^3\,m^{-3}$ for SWC and 360 g DM m^{-2} for yield, as well as negative modelling efficiencies and some high relative root mean square errors indicate low model performance, especially for biomass. We also found substantial discrepancies across different models, indicating considerable uncertainties regarding the simulation of grassland processes. The multi-model approach allowed for improved performance, but further progress is strongly needed in the way models represent processes in managed grassland systems.

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1. List of the most important symbols and abbreviations used in the paper

Symbol/abbreviation	Long version	Explanation
b	Aridity index	Agro-climatic metric
hw	Heat wave days frequency	Agro-climatic metric
GRI	Grillenburg	Grassland site
OEN	Oensingen	Grassland site
LAQ	Laqueuille	Grassland site
MBO	Monte Bondone	Grassland site
KEM	Kempten	Grassland site
LEL	Lelystad	Grassland site
MAT	Matta	Grassland site
ROT	Rothamsted	Grassland site
SAS	Sassari	Grassland site
AnnuGrow	Process-based model of the growth of annual plants in drylands	Grassland model
ARMOSA	Monitoring and modelling nitrogen cycle and crop growth in arable land	Grassland model
Biome-BGC MuSo	Biogeochemical cycles with multi-layer soil module	Grassland model
CARAIB	Carbon Assimilation in the Biosphere	Grassland model
EPIC	Environmental Policy Integrated Climate	Grassland model
LPJmL	Lund–Potsdam–Jena managed Land	Grassland model
PaSim	Pasture Simulation model	Grassland model
SPACSYS	Soil Plant Atmosphere Continuum System	Grassland model
STICS	Multidisciplinary simulator for standard crops	Grassland model
DM	Dry matter	Output variable
ET	Actual evapotranspiration	Output variable
GPP	Gross primary production	Output variable
HAB	Harvested aboveground biomass	Output variable
NEE	Net ecosystem exchange	Output variable
RECO	Total ecosystem respiration	Output variable
SAB	Standing aboveground biomass	Output variable
ST	Soil temperature	Output variable
SWC	Soil water content	Output variable
BIAS	Mean difference of simulations and observations	Performance metric
ME	Modelling efficiency	Performance metric
R^2	Coefficient of determination of the linear regression estimates versus measurements	Performance metric
RRMSE	Relative root mean square error	Performance metric
ER	Ensemble ratio	Uncertainty metric

2. Introduction

Grasslands are widespread vegetation types worldwide (about 40.5% of the Earth's landmass; Suttie et al., 2005), covering a large proportion of the European continent (67 million ha in the EU-27 that is 40% of agricultural land, 15% of total area, 85% of which being occupied by permanent grasslands, Peeters, 2012; Peyraud, 2013). Pastoral lands contribute to agricultural production and ecosystem services, including the provisioning of forage and, hence, of milk and meat (Huyghe, 2008). In addition, permanent grasslands are often hotspots of biodiversity (Marriott et al., 2004), which contributes to the temporal stability of their services.

Grassland biomass yield is an important agro-technical indicator to evaluate the economic viability of grassland-based milk and meat production systems (e.g. Schader et al., 2013). Adaptation of grasslands to climate change, for instance, includes adaptation to climatic variability and extremes to minimize fluctuations in biomass supply (Collins, 1995). Considering the viability of grassland-based systems depending on their ability to produce meat from forage harvested on-farm, it is critical to examine the dynamics of grassland biomass production, where management plays a role by influencing the temporal forage availability and the interactions between herd and grassland.

Grassland ecosystem models have become important tools for extrapolating local observations and testing hypotheses on grassland ecosystem functioning (Chang et al., 2013; Graux et al., 2013; Vital et al., 2013; Ma et al., 2015). Under the auspices of the FACCE MACSUR knowledge hub (http://macsur.eu), a model intercomparison was conducted using datasets from an observational and experimental network of nine multi-year flux and production sites spread across Europe (France, Italy, Germany, Switzerland, The Netherlands, and United Kingdom) and Israel, and engaging a modelling community using a suite of different models to understand grassland functioning. In particular, the collected datasets of meteorological data, C, energy and water fluxes were used to drive and evaluate the performance of nine grassland models.

The identified models are an inventory of modelling approaches made available through the MACSUR consortium and applied worldwide. Grassland-specific approaches were used together with other approaches, mainly conceived to simulate crops and plant functional types. The primary goal of this study is to synthesize and compare the participating grassland models to assess current understanding of soil processes (soil temperature and soil water content, which are fundamental drivers of ecosystem-scale processes) and aboveground/harvested biomass (which is the output of major significance in agricultural production) in Europe and Israel. To achieve this goal, model evaluation against actual measurements was performed before and after model calibration. To the best of authors' knowledge, this is the first model intercomparison performed specifically on permanent grasslands. The present study, focused on grassland sites across Europe and a neighbour country (Israel) for which complete sets of data were provided by the MACSUR consortium, extends preliminary analyses (Ma et al., 2014; Sándor et al., 2015), and parallels other initiatives on the comparison of grassland models worldwide, such as the Agricultural Model Intercomparison and Improvement Project (AgMIP, Rosenzweig et al., 2013) and other international projects (Soussana et al., 2015).

The present grassland model intercomparison tries to answer five fundamental questions in a multi-site, multi-model framework: (1) are the main drivers of grassland processes represented well by state-of-the-art grassland models? (2) what are the skills of the studied models with respect to their basic processes? (3) can calibration improve the models in terms of quality of simulation of different processes? (4) can the ensemble of model results be used to estimate soil properties and grassland biomass in the study sites? and (5) what uncertainties are associated with the different models, and how can uncertainty be quantified in a multi-model framework? In addition, areas are identified where structural changes in models may be needed to improve performances and decrease uncertainty of process representation.

3. Material and methods

3.1. Study sites

The nine long-term grassland sites used for the modelling exercise (Table 1) cover a broad range of geographic and climatic conditions (Fig. 1; see also Fig. A and Table A1 in the Supplementary material, Section 1) as well as a variety of management practices (Table A2 in the Supplementary material, Section 1). The sites rep-