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The grassland model intercomparison of the MACSUR (Modelling European Agriculture with Climate Change for Food Security) European knowledge hub

Shaoxiu Ma[a], Marco Acutis[b], Zoltán Barcza[c,d], Haythem Ben Touhami[a], Luca Doro[e], Dóra Hidy[f], Martin Köchy[g], Julien Minet[h], Eszter Lellei-Kovács[c], Alessia Perego[b], Susanne Rolinski[i], Françoise Ruget[j], Giovanna Seddaiu[e], Lianhai Wu[k], Gianni Bellocchi[a]

[a]*French National Institute for Agricultural Research, Grassland Ecosystems Research Unit, Clermont-Ferrand, France*
[b]*University of Milan, Department of Agricultural and Environmental Sciences - Production, Landscape, Agroenergy, Milan, Italy*
[c]*Institute of Ecology and Botany, MTA Centre for Ecological Research, Vácrátót, Hungary*
[d]*Eötvös Loránd University, Department of Meteorology, Budapest, Hungary*
[e]*University of Sassari, Desertification Research Centre, Sassari, Italy*
[f]*Szent István University, MTA-SZIE Plant Ecology Research Group, Gödöllő, Hungary*
[g]*Thünen Institute of Market Analysis, Braunschweig, Germany*
[h]*University of Liège, Arlon Environment Campus, Arlon, Belgium*
[i]*Potsdam Institute for Climate Impact Research, Potsdam, Germany*
[j]*French National Institute for Agricultural Research, Modelling Agricultural and Hydrological Systems in the Mediterranean Environment, Avignon, France*
[k]*Rothamsted Research, North Wyke, Okehampton, United Kingdom*

Email address: gianni.bellocchi@clermont.inra.fr

Abstract: The grassland model intercomparison of the FACCE MACSUR knowledge hub involves nine modelling approaches. Grassland-specific approaches (AnnuGrow, PaSim, SPACSYS) are compared to the approaches mainly conceived to simulate crops (ARMOSA, EPIC, STICS) and biomes (Biome-BGC MuSo, CARAIB, LPJmL). The model intercomparison exercise is run over nine grassland sites across Europe and peri-Mediterranean regions where data were collected from at least five, up to 31 years, with focus on biomass production and carbon exchanges. The protocol for model intercomparison, derived from AgMIP - Agricultural Model Intercomparison and Improvement Project, includes sensitivity tests, as well as blind and calibrated simulations. A fuzzy-logic based indicator for model assessment was developed providing insights into agreement between simulations and observations, complexity of model structure and robustness of simulation results over a variety of conditions. Some results are anticipated and show the limitations of the modelling undertaken thus far with current parameterization to simulate grassland dry matter and C exchanges across the Euro-Mediterranean region. The study also suggests that the regional calibration can accommodate model discrepancies. However, areas in the model structures have been identified that require further improvements to reduce uncertainties and increase reliability of model results in impact studies.

Keywords: Grassland; Evaluation; Intercomparison; Modelling

1. INTRODUCTION

The MACSUR (Modelling European Agriculture with Climate Change for Food Security, http://www.macsur.eu) knowledge hub, established within the Joint Programming Initiative on Agriculture, Food Security and Climate Change (FACCE-JPI, http://www.faccejpi.com), brings together 74 organizations from 17 European countries and Israel. Its mission is to facilitate the creation of collaborative, inter-disciplinary structures for research and global, multi-sectorial problems such as climate change (Soussana et al., 2012). The goal of MACSUR is to develop a pan-European agricultural modelling capability, bringing together modelling teams to improve the accuracy of predictions of the effects of climate change, and reveal the adaptation and mitigation potential on European agro-ecosystems. Process-based models represent a good way for studying the effects of weather patterns in great detail and projecting consequences of climate change, which would be hard to achieve in experiments. The project connects crop (CropM theme), livestock and grassland (LiveM theme) and trade (TradeM theme) modellers to collate, share and evaluate datasets for modelling, develop methods of model intercomparison, explore ways to improve the impact and relevance of modelling outputs, and scale up model predictions to the regional level. A previous paper detailed the priorities and opportunities for CropM (Rötter et al. 2013). Kipling et al. (2014) focussed on LiveM, which deals with modelling livestock systems, including grasslands. The paper presented here focuses on grassland modelling activities, i.e. 1) building and exploring datasets at European (and peri-European) grassland sites; 2) identifying a list of grassland models for use in impact assessment studies. The datasets collected (section 2) illustrate a bunch of data covering a variety of climate and management conditions. The models identified (section 3) are an inventory of modelling approaches made available through the MACSUR consortium and applied across Europe and peri-Mediterranean regions. Section 4 illustrates model intercomparison and evaluation protocols. Section 5 anticipates some results, and section 6 highlights the value and limits of the study and future research needs.

2. GRASSLAND DATASETS

Long-term (five to 31 years of data) grassland sites were identified (Bellocchi et al., 2013), covering a gradient of geographic and climatic conditions (Figure 1, left) and a variety of management practices. Four of them (Laqueuille, France, Klumpp et al., 2011; Monte Bondone, Italy, Wohlfahrt et al., 2008; Grillenburg, Germany, Prescher et al., 2010; Oensingen, Switzerland, Amman et al., 2007), equipped with eddy covariance systems to determine the net ecosystem exchange of CO_2, are semi-natural grasslands in place for a long time including vegetation types representative of the zone (with the exception of Oensingen, established in 2001). Other sites (Kempten, Germany, Schröpel and Diepolder, 2003; Lelystad, The Netherlands, Schils and Snijders, 2004; Matta, Israel, Golodets et al., 2013; Rothamsted, United Kingdom, Sylverston et al., 2006; Sassari, Italy, Cavallero et al., 1992) from experimental research focus on biomass production. The limits of the De Martonne-Gottmann index (*b*, De Martonne, 1942) discriminate between aridity conditions (Figure 1, right): b<5: extreme aridity; 5≤b≤14: aridity; 15≤b≤ 19: semi-aridity; 20≤b≤29: sub-humidity; 30≤b≤59: humidity; b>59: strong humidity (Diodato and Ceccarelli, 2004).

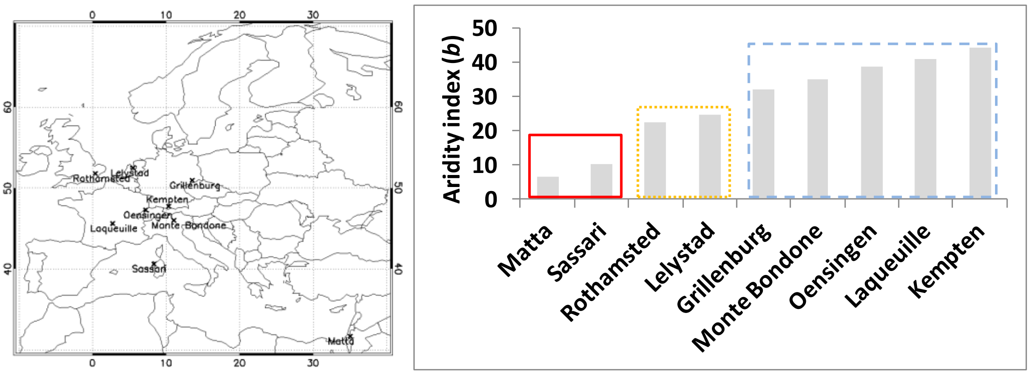

Figure 1. Geographic location (left) and classification (right) of grassland sites with respect to De Martonne-Gottmann aridity index (*b*). The solid box, dotted box and hatched box represent arid, sub-humid and humid sites, respectively.

3. GRASSLAND MODELS

Nine models were identified for the intercomparison (Bellocchi et al., 2013).
Three of them are **grassland-specific models**. **AnnuGrow** (Köchy, 2008) quantifies the effect of daily rainfall distributions and compares it to the effect of a change in mean annual amount on vegetation. **PaSim** (Ma et al., 2014) simulates water, carbon and nitrogen cycles in grassland plots at sub-daily time step via modules of climate, soil biology and physics, vegetation and management (including grazing animals). **SPACSYS** (Wu et al., 2007) is a multi-dimensional, field-scale, daily time-step model of carbon and nitrogen cycles between plants, soils and microbes, with fine representation of the root system.
The following are **crop models** with grassland options. **ARMOSA** (Perego et al., 2013) estimates nitrogen dynamics in soil-crop-atmosphere continuum and evaluates the impact of management on shallow and groundwater quality via modules of energy, water, carbon and nitrogen balances, and plant development and growth. **EPIC**, originally developed to estimate soil productivity as affected by erosion (Williams et al., 2008), is designed to allow simulation of a large variety of crops and grasses with unique parameter values. **STICS** (Brisson et al., 2003) is a generic, daily-step, patch-scaled model covering many crops and conditions of climate, soil and management, being set to simulate either sown or established mowed grasslands.
Three **biome models** include grasslands as biome type. **Biome-BGC MuSo** (Hidy et al., 2012) implements a multilayer soil module, improved grassland phenology and management routines into the Biome-BGC, originally developed to simulate undisturbed ecosystems, with allometric relationships used to initialize carbon and nitrogen pools. **CARAIB** (Warnant et al., 1994), a process-based vegetation model of carbon assimilation in the biosphere, implements a range of plant functional types including C_3 and C_4 grasses. Based on the LPJ-Dynamic Global Vegetation Model, **LPJmL** simulates vegetation composition and distribution as well as stocks and land-atmosphere exchange flows of carbon and water (Waha et al., 2012) using generic crop functional types to represent plant prototypes.

4. PROTOCOLS FOR MODEL INTERCOMPARISON AND EVALUATION

A protocol based on the principles laid down by the Agricultural Model Intercomparison and Improvement Project (AgMIP, http://www.agmip.org), includes: **evaluation of uncalibrated (blind) and calibrated model simulations** against observations, and **sensitivity tests** of models to changes of CO_2, temperature and precipitation.
Fuzzy-logic based multi-metric evaluation indicators (between 0, best and 1, worst) are applied for model evaluation at multiple sites (Acutis and Bellocchi, 2014),

designed in three modules. The module **Agreement** is made of Pearson's correlation coefficient between predictions and observations, Willmott's index of agreement, and Student-t probability of equal means for paired data. The module **Complexity** is made of relevant over total parameters ratio, and a weighed measure of the Akaike's Information Criterion. For both **Agreement** and **Complexity**, metrics values are the average of values from the simulations at multiple sites. The module **Robustness** is made of an index of the robustness of model performance over a variety of sites, depending on site precipitation and reference evapotranspiration.

5. ILLUSTRATIVE RESULTS

It is not the intention of the model intercomparison to qualify or assess the performance of each single model and therefore, the outcomes of some illustrative tests are presented anonymously, with models indicated by 1 to 9 with no relation holding between any number and any model (only a relation to the type of model is used to illustrate results).

5.1 Uncalibrated simulations

Blind simulations of harvested biomass at Rothamsted (United Kingdom), a multi-year experimental site (with cuts in June and November and fertilized with 48 kg N ha^{-1} yr^{-1} in April), show that some models (grassland model 4, crop models 6 and 8) approach the observations with far less bias than others (Figure 2).

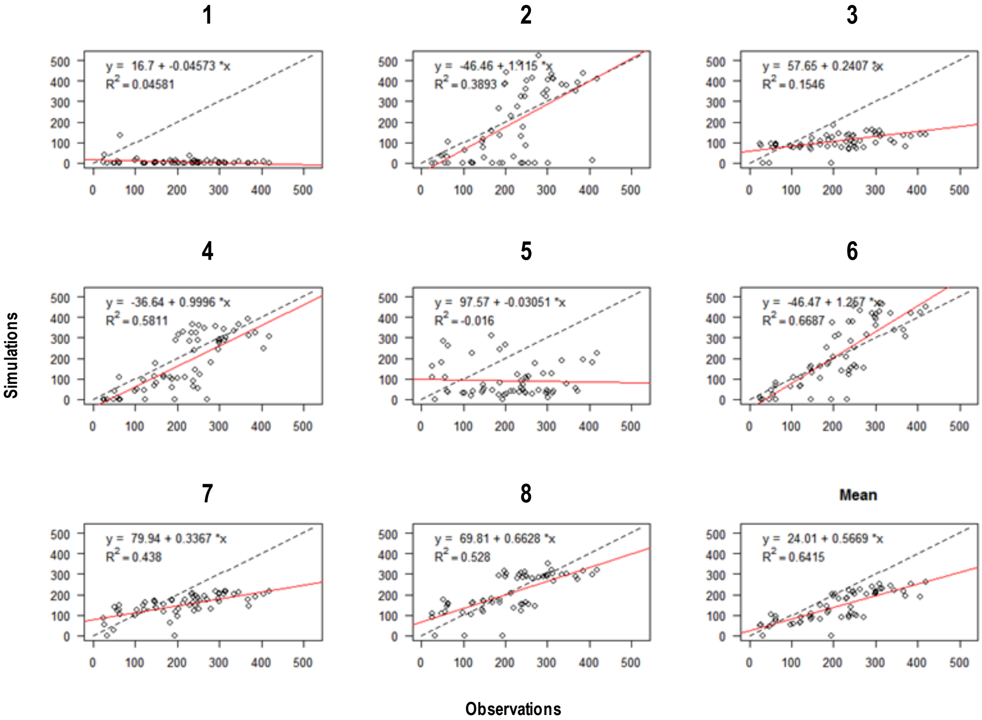

Figure 2. Blind tests: simulated (eight models and the mean output from all models) versus observed harvested above ground biomass (g DM m^{-2}) at Rothamsted (1981-2011), United Kingdom (solid line: linear regression between simulations and observations; hatched line: 1:1 line).

Another example (Figure 3) refers to gross primary production (GPP, monthly values), blindly simulated by five models and compared to observations at the

Swiss site of Oensingen, where the grassland is mowed 3-4 times each year and highly fertilized (more than 200 kg N ha^{-1} yr^{-1} split into four events).

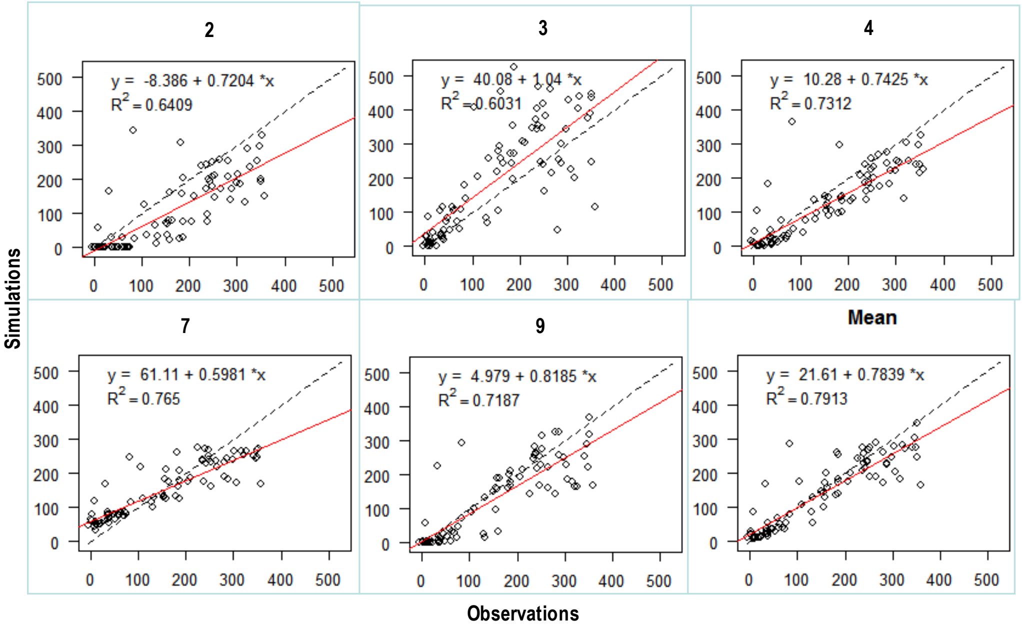

Figure 3. Blind tests: simulated (five models and the mean output from all models) versus observed gross primary production (g C m^{-2} $month^{-1}$) at Oensingen (2002-2009), Switzerland (solid line: linear regression between simulations and observations; hatched line: 1:1 line).

Regression lines (Figure 3) indicate that blind parameterizations roughly match GPP observations for all models (slope and intercept near 1 and 0, respectively; adjusted R^2>0.6), although some calibration would help to improve performances. The uncertainty envelope obtained with the ensemble of model estimates (Figure 4) shows that the influence of extreme events such as the hot and dry summer 2003 can lead to an amplification of uncertainties.

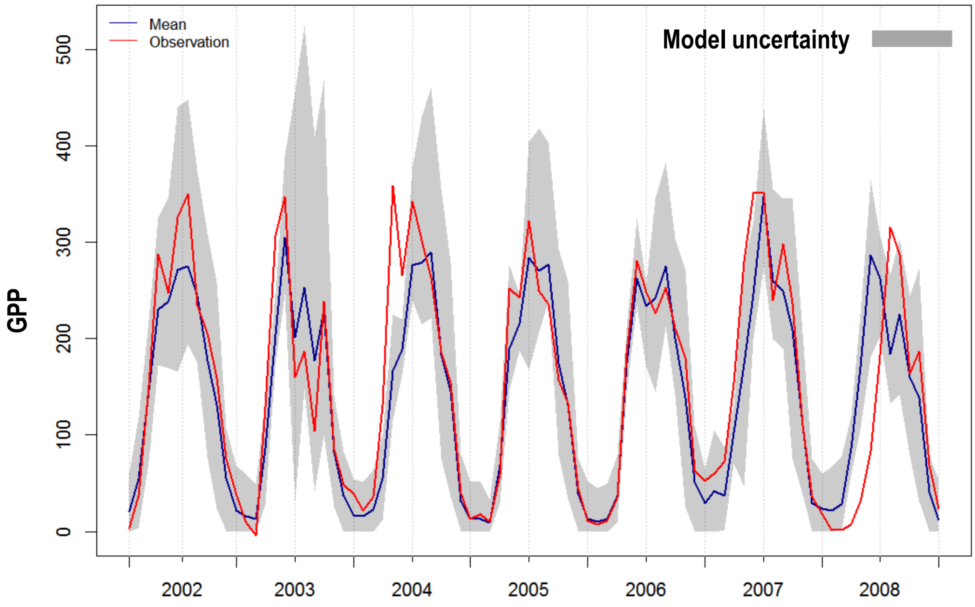

Figure 4. Blind tests: fluctuations of simulated (mean of five models) and observed gross primary production (GPP, g C m^{-2} $month^{-1}$) at Oensingen (2002-2009), Switzerland, with the envelope of uncertainties from the ensemble of models.

5.2 Calibrated simulations

Compared to the blind test for GPP (Figure 3), the performance of model 2 (biome model) improved with calibration (Figure 5). For model 4 (grassland model), calibration did not improve predictive skills because the previous parameterization was already well employed in European grasslands.

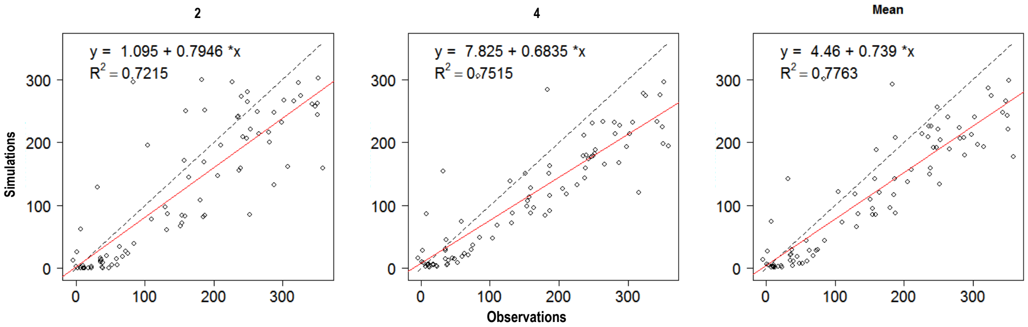

Figure 5. Calibrated tests: simulated (two models and the mean output from both models) versus observed gross primary production (g C m^{-2} month^{-1}) at Oensingen (2002-2009), Switzerland (solid line: linear regression between simulations and observations; hatched line: 1:1 line).

5.3 Sensitivity tests

The behaviour of models when changing environmental factors was also investigated. For grassland model 4, Figure 6 shows that the annual GPP (average over 2004-2010) increased by about 35%, with increase in atmospheric CO_2 concentration from 380 to 760 ppmv (which closely reflect the sensitivity of C_3 plant species documented by literature, e.g. Ainsworth and Rogers, 2007).

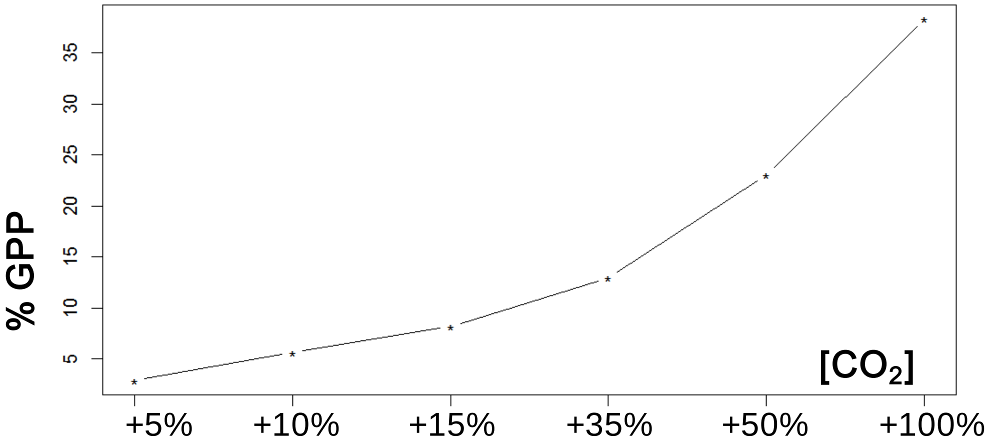

Figure 6. Relative changes of gross primary production (GPP, g C m^{-2} yr^{-1}) estimated with model 4 at Laqueuille, France, over a gradient of CO_2 concentrations (baseline: 380 ppmv).

6. CONCLUSION AND PERSPECTIVES

This study, focused on various sites across Europe and peri-Mediterranean regions, extends parallel initiatives on the comparison of grassland models worldwide, such as AgMIP and other international projects (https://colloque.inra.fr/workshop_gra_jpi_facce_eng/2-Model-Intercomparison). The results shown are illustrative of the methodology adopted for grassland model intercomparison in MACSUR. The insights gained from this ongoing study are relevant for some crop and biome models, which proved comparable to grassland-specific models to simulate biomass data from managed grasslands (even with blind simulations). Calibration can improve model performance, though some limitations in the representation of processes require advances in modelling capabilities (e.g. inclusion of new functions to account for extreme climate events). The results reported here cannot be considered conclusive. The analyses are still ongoing and additional results will be published as they become available, as well as the comprehensive evaluation of models with fuzzy-logic based indicators.

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